



International Agreement Report

Modification of USNRC's FRAP-T6 Fuel Rod Transient Code for High Burnup VVER Fuel

Prepared by

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ABSTRACT

The USNRC's transient fuel rod code, FRAP-T6, has been modified to analyze pulse tests with high burnup VVER fuel rods in the Impulse Graphite Reactor (IGR). New and modified models of separate phenomena have been developed, including models for heat transfer from the cladding to the stagnant coolant, the effect of fission gas swelling on the fuel-cladding gap, and the conditions of base irradiation. Thermal and mechanical properties for the VVER's Zr-1%Nb cladding were added to MATPRO-V11, which is used by the FRAP-T6 code. Changes in the input data file are described, and a sample calculation is presented with the modified code. A FORTRAN listing for the new and modified models is given in an Appendix A.

TABLE OF CONTENTS

1. INTRODUCTION.....	4
2. THERMAL DYNAMICS	6
2.1. THE MODEL TO ANALYZE POWER RATE IN THE FUEL WITH CENTRAL HOLE	6
2.2. ALTERNATIVE MODEL OF HEAT TRANSFER UNDER FILM BOILING	6
2.3. THE MODEL OF CLAD-TO-AIR HEAT TRANSFER	7
2.4. THE MODEL OF THE CLADDING REWETTING	8
3. THERMAL MECHANICS	10
3.1. ACCOUNTING FOR THE FUEL GAS SWELLING WHEN ANALYZING FUEL-CLADDING GAP SIZE.....	10
3.2. CLADDING BALLOONING MODEL	10
4. FISSION GAS BEHAVIOR.....	12
4.1. APPROACH TO ANALYZE FISSION GAS BEHAVIOR UNDER BASE IRRADIATION CONDITIONS	12
4.1.1. <i>Fuel swelling due to accumulation of the fission products</i>	12
4.1.2. <i>Irradiation-induced fuel densification</i>	13
4.1.3. <i>Dependence of the power rate radial non-uniformity versus time</i>	13
4.2. INITIAL DATA AND THE PROCEDURE TO ANALYZE FISSION GAS BEHAVIOR UNDER THE BASE-CONDITIONS.....	13
4.2.1. <i>Extension of the power history array</i>	13
4.2.2. <i>The method to specify input data for the analysis of base irradiation</i>	13
4.2.3. <i>Analysis of the fuel rod behavior under base irradiation conditions</i>	13
5. ALTERNATIVE THERMAL - PHYSICAL MATERIAL PROPERTIES (MATPRO-V11 LIBRARY EXTENSION)	15
5.1. THERMAL-PHYSICAL PROPERTIES OF FUEL	16
5.1.1. <i>Fuel specific heat (FCP) and enthalpy (FENTHL)</i>	16
5.1.2. <i>Thermal expansion (FTHEXP)</i>	17
5.1.3. <i>Thermal conductivity of the VVER type of UO₂, and dependence of thermal conductivity versus fuel burnup (FTHCON, BURNUP, TCOR)</i>	18
5.1.4. <i>Thermal-physical constants (PHYPRP)</i>	19
5.2. THERMAL-PHYSICAL PROPERTIES OF Zr-1%Nb CLADDING	20
5.2.1. <i>Thermal-physical constants (PHYPRP)</i>	20
5.2.2. <i>Specific heat (CCP) and enthalpy (CCINP)</i>	20
5.2.3. <i>Thermal expansion (CTHEXP)</i>	21
5.2.4. <i>Thermal conductivity (CTHCON)</i>	23
5.2.5. <i>High temperature oxidation (COBILD)</i>	24
5.3. MECHANICAL PROPERTIES OF Zr-1%Nb CLADDING	25
5.3.1. <i>Young's modulus (CELMOD) and Poisson's ratio (EMCPIR)</i>	25
5.3.2. <i>Meyer micro-hardness (CMHARD)</i>	26
5.3.3. <i>Plastic deformation of the cladding (CKMN)</i>	26
5.3.4. <i>Cladding failure criterion (CMLIMT)</i>	29
6. CODING ASPECTS	31
6.1. DESCRIPTION OF THE NEW GLOBAL VARIABLES	31
6.2. DESCRIPTION OF THE NEW AND MODIFIED SUBROUTINES	35
7. USER'S MANUAL	38
7.1. DESCRIPTION OF THE NEW INPUT DATA	38

7.2. DESCRIPTION OF THE OUTPUT INFORMATION	42
7.2.1. Output file FGR_AXIS.DAT	42
7.2.2. Output file FGR_TRAN.DAT and FGR_TOT.DAT.....	43
7.2.3. Output files FGR_RADS.DAT and FGR_RADT.DAT.....	43
7.2.4. Output files BALOON1.DAT, BALOON2.DAT.....	44
7.2.5. Output file GRAPH.DAT.....	45
7.2.6. File BRIEF.OUT (brief listing).....	47
7.2.7. Post-processing utility for the STRIPF file	49
7.3. COMMENTS ON THE USERS AND DEVELOPERS OF FRAP-T6/VVER CODE	50
7.3.1. The limits for applicability of the adapted FRAP-T6/VVER code.....	50
7.3.2. Further development of the adapted version of FRAP-T6 code.....	51
8. CALCULATION EXAMPLES.....	52
8.1. THE EXAMPLE OF CALCULATED RESULTS OF THE VVER FUEL ROD BEHAVIOR UNDER TESTING CONDITIONS IN IGR REACTOR	52
REFERENCES	56
APPENDIX A. List of new and modified subroutines of FRAP-T6/VVER codeA-1	
APPENDIX B. The revealed mistakes.....	B-1

1. INTRODUCTION

In the Russian Research Center "Kurchatov Institute", the behavior of high burnup VVER-type fuel rods was studied under conditions of reactivity-initiated accidents. Testing of these fuel rods in the Impulse Graphite Reactor (IGR) led to a number of special features. A single fuel rod with an active length of ~ 150 mm and filled with helium (1.6-2.3 MPa) was put in a capsule that was filled with stagnant coolant (water or air) at room pressure and temperature. This capsule was put in the IGR reactor central channel, and the reactor power was pulsed with a pulse width of 0.7-0.9 sec to simulate a reactivity accident. A large number of tests like this were performed, and they are described in a separate report [1].

A transient fuel rod code was sought to analyze the test data and provide the capability to perform related safety transient calculations. Two codes were obtained for this purpose. One was the USNRC's FRAP-T6 transient fuel rod code developed at the Idaho National Engineering Laboratory (USA) [2]. The other was the IPSN's (Institute for Protection and Nuclear Safety (France)) SCANAIR transient fuel rod code developed at the Cadarache Center for Studies (France) [3]. Both codes required modification for this application. Modifications to the FRAP-T6 code are described in this report, and modifications to the SCANAIR code are described in another report [4].

FRAP-T6 code models the following main accident phenomena:

1. change of thermal-mechanical properties of the fuel and cladding materials of the LWR reactor type versus temperature, burnup, etc.;
2. distribution of temperatures in the fuel rod considering the change of thermal conductivity of the fuel-cladding gap, connected with the change of the gap size and gas composition due to the fission product release out of fuel;
3. stress-strain state of the fuel cladding in the assumption of the «thin-walled» cladding, including the stage of fuel-cladding mechanical interaction. In this case thermal expansion is modeled, elastic deformation, deformation of the cladding plasticity, as well as thermal expansion of the fuel pellet;
4. cladding failure;
5. high-temperature oxidation of the cladding;
6. fission gas behavior in the fuel rod, gas swelling of the fuel, change of the gas composition and pressure inside the cladding;
7. water coolant behavior, and heat transfer from the fuel cladding to the water.

FRAP-T6/v.21/90 version of the code was used for the analysis. Two main tasks were to be solved in order to adapt FRAP-T6 code to the conditions of the VVER fuel rod testing in IGR reactor:

1. to account for specific features of the high burnup VVER fuel rods;
2. to validate FRAP-T6 code for the conditions of the capsule testing.

The following features of the IGR tests were identified to solve the first task:

1. use of the fuel rods of VVER. This required introduction of thermal-physical and mechanical properties of VVER fuel and Zr-1%Nb cladding into MATPRO-V11 [5] data base of material properties;
2. testing of high burnup fuel rods. This required introduction into FRAP-T6 code of a number of models for preliminary analysis of the fuel rod behavior under the base irradiation conditions; such calculations were necessary to get the data on the fission gas distribution in the fuel at the end of the basis irradiation mode. The obtained data were used as input data when modeling the IGR tests;
3. use of the air coolant in some tests. This required introduction into FRAP-T6 code of the heat transfer models with free circulation of the gas coolant and thermal-physical properties of the air.

Verification of the code including the use of the data obtained with the help of instrumented fuel rods was necessary in order to solve the second task. Verification results were used to modify some of the models of

FRAP-T6 code. Comparison of the obtained calculated and experimental data allowed to reveal a number of models requiring adaptation to the specific features of the IGR tests. In particular, the alternative models to calculate gas gap size, and the models for heat transfer from the cladding to the water coolant in the regimes of film boiling and rewetting of the cladding were developed.

A general description of the computer code modifications for FRAP-T6 and SCANAIR, along with calculations, material properties, and the data base for validation, are given in another report [1]. The details of the FRAP-T6 modification are given here.

The second chapter of the report describes modifications of the thermal-physical package of FRAP-T6 code to account for specifics of the design of VVER fuel rods tested in IGR reactor, and for the specifics of the fuel rod cooling in the capsule experiments. Adaptive models of heat transfer to the water and air coolants, and thermal-physical properties of the air coolant are presented.

The third chapter of the report presents the changes made to thermal-mechanical block of the code for the better analysis of both thermal-physical and thermal-mechanical parameters of the burnup fuel rod in the case of the accident. The model accounting for the influence of the fuel pellet gas swelling onto the gas gap size is presented.

The fourth chapter reviews modifications of the model describing fission product behavior in the fuel under the conditions of base irradiation. The above modifications were necessary to obtain the data on distribution of fission gas accumulated in fuel in the process of burnup. These are the input data when modeling testing of the burnup fuel rods in IGR reactor.

The fifth chapter presents thermal-physical and thermal-mechanical material properties of the VVER fuel rods, that were included into MATPRO-V11 base of material properties used by FRAP-T6/VVER code.

The sixth chapter reviews the aspects of programming connected with the new version of FRAP-T6/VVER code. New global variables, new and modified subroutines are described.

The seventh chapter is the user's manual on the practical application of the version. It includes description of the new input data, alternative program to process the output information, and recommendations to the users of FRAP-T6/VVER code to model fuel rod behavior under the conditions of pulse testing in IGR reactor. The chapter also includes proposals and recommendations of the authors to the further broadening of the capabilities of FRAP-T6/VVER code to model RIA processes.

The example of calculated results of the VVER fuel rod behavior under test conditions in IGR reactor given in chapter eight demonstrates the limits of applicability of the developed version and can be used for checking correctness of FRAP-T6/VVER version. Example of the nodalization scheme to model the fuel rod by FRAP-T6/VVER code is presented.

Appendix A presents a FORTRAN listing of the subroutines described in chapter 6 and containing new and adaptive models, as well as the example of the input deck file. Bugs found in the texts of FRAP-T6 subroutines are listed in Appendix B.

2. THERMAL DYNAMICS

FRAP-T6 code performs the analysis of the non-steady-state temperature field in the fuel rod with consideration of the changes of the geometrical sizes of the fuel pellet and cladding in the radial direction during the accident.

New models to specify power rate in fuel with central hole during base irradiation and heat transfer from the fuel cladding to the coolant are added in order to adapt thermal-physical block of FRAP-T6 code to the specifics of IGR/VVER processes. Model of heat transfer under the conditions of free convection of the gas coolant, and thermal-physical properties of air are incorporated into code as an additional model of clad-to-air heat transfer.

2.1. The model to analyze power rate in the fuel with central hole

The method to analyze power rate was changed for correct consideration of the radial power rate in the fuel pellet with central hole. In the initial version of FRAP-T6 code it is possible to input the radius of the central hole, the volume of which is considered for the analysis of internal gas pressure of fuel rod. Still, when calculating power rate radial distribution it is not considered that no heat is generated in the central hole. This drawback is corrected in the proposed model for the analysis of the power rate radial profile in the fuel.

RINTIM, FINT, RIMMOD subroutines contain alternative method to specify input data on power rate in fuel with the central hole. RIMMOD subroutine is developed on the base of PRAD subroutine from original FRAP-T6 code. FORTRAN text of this subroutines is presented in Appendix A.

2.2. Alternative model of heat transfer under film boiling

In accordance with verification calculations [1] the model to calculate post-critical heat transfer coefficient based on Bromley-Pomerantz [2] correlation was replaced with the Labuntzov model. Labuntzov model, developed for the turbulent regimes of film boiling and modified to account for the boiling conditions of the large volume of subcooling water is [6]:

$$\alpha_{FB} = 0.25(\lambda_g^2 c_{pg} (\rho_f - \rho_s) \frac{g}{\nu_g})^{1/3},$$

Where α_{FB} = heat transfer coefficient ($\text{W}/\text{m}^2\text{K}$);

λ_g = vapor thermal conductivity ($\text{W}/\text{m K}$);

c_{pg} = vapor specific heat ($\text{J}/\text{kg K}$);

ρ_f = fluid density (kg/m^3);

ρ_s = vapor density (kg/m^3);

g = gravity acceleration (m/s^2);

ν_g = vapor kinematic viscosity (m^2/s).

To take into account the initial subcooling of water, the correction factor is introduced [7]:

$$\alpha_{FB}^* = \alpha_{FB} \left(1 + 0.1 \left(\frac{\rho_f}{\rho_s}\right)^{0.75} \frac{\Delta i}{h_{fg}}\right),$$

where α_{FB}^* = corrected heat transfer coefficient ($\text{W}/\text{m}^2\text{K}$);

Δi = enthalpy of fluid at saturation minus enthalpy at fluid bulk temperature (J/kg);

h_{fg} = latent heat (J/kg).

Alternative model of the film boiling is included into QDOT subroutine called by HTRC subroutine, text of which is presented in Appendix A.

2.3. The model of clad-to-air heat transfer

There exists the capability in HTRC subroutine to model heat transfer coefficient from the fuel rod to helium coolant in the conditions of forced lengthwise circulation in the bundle of rods. HTRC subroutine also has the respective base of the helium thermal-physical properties. But in the code there is no heat transfer model for the conditions of large volume of stagnated air coolant.

Heat transfer model, which is a part of QDOT subroutine, called by HTRC subroutine consists of two parts: free convection heat transfer and heat transfer due to radiation.

$$h = h_{con} + h_{rad},$$

where h_{con} = heat transfer coefficient due to convection;

h_{rad} = heat transfer coefficient due to radiation (the code already has this model).

Heat transfer coefficient due to convection can be determined by the system of the following equations [8]:

$$Nu = CRa^n, \quad Ra = GrPr,$$

$$Gr = \frac{g\beta(t_w - t_f)z^3}{v \cdot a},$$

$$h_{con} = \frac{\lambda Nu}{z},$$

where Nu , Ra , Gr , Pr = Nusselt number, Rayleigh number, Grashof number, Prandtl number, respectively;

g = acceleration due to gravity (m/s^2);

β = thermal expansion volumetric coefficient ($1/\text{K}$);

z = heating length (m);

t_w = wall temperature (K);

t_f = fluid temperature (K);

C, n = coefficients;

λ = thermal conductivity ($\text{W}/\text{m K}$);

h_{con} = heat transfer coefficient due to convection ($\text{W}/\text{m}^2\text{K}$);

v = kinematic viscosity (m^2/s);

a = temperature conductivity (m^2/s).

Nu, Ra, Gr, Pr are calculated at the temperature:

$$t_m = \frac{(t_w + t_f)}{2},$$

C, n coefficients are identified according to the data of Table 2.1.

Table 2.1. C, n coefficients vs. Ra, Pr.

Ra	Pr	C	n
$10^3 - 10^9$	0.1	0.32	0.25
	1.0	0.54	0.25
	10	0.62	0.25
	100	0.66	0.25
$10^9 - 10^{13}$		0.15	0.333

Heat flux due to heat transfer by radiation from the fuel cladding to the capsule wall is analyzed with the use of FRAP-T6 original model.

The following thermal-physical properties of the air are used in the form of polynomials versus temperature [8]:

$$\lambda = 24.407 + 7.978 \cdot 10^{-2} \cdot t - 3.154 \cdot 10^{-5} \cdot t^2 + 0.802 \cdot 10^{-8} \cdot t^3,$$

$$c_p = 1004.16 - 9.761 \cdot 10^{-3} \cdot t + 55.229 \cdot 10^{-5} \cdot t^2 - 36.275 \cdot 10^{-8} \cdot t^3,$$

$$\alpha = 10^{-6} \cdot (18.788 + 13.484 \cdot 10^{-2} \cdot t + 13.959 \cdot 10^{-5} \cdot t^2 - 4.654 \cdot 10^{-8} \cdot t^3),$$

$$\mu = 10^{-6} \cdot (17.162 + 49.894 \cdot 10^{-3} \cdot t - 2.935 \cdot 10^{-5} \cdot t^2 + 1.133 \cdot 10^{-8} \cdot t^3),$$

$$\rho = -2.883 \cdot 10^{-3} + 355.06/(t + 273) + 353.527/(t + 273)^2,$$

where λ = thermal conductivity (W/m K);

c_p = specific heat (J/kg K);

α = temperature conductivity (m^2/s);

μ = dynamic viscosity (Pa s);

ρ = density (kg/m^3);

t = average between temperature heated wall and coolant ($^{\circ}C$).

2.4. The model of the cladding rewetting

The moment for the beginning of the rewetting is determined by the model developed in RRC «KI» [9]. The option for analyzing of the rewetting moment is specified in the input data file. Heat transfer coefficient in the mode of transfer from the film to the nucleate boiling is defined by the linear interpolation between two points in the boiling curve. The first point corresponds to the heat transfer coefficient at film boiling at the moment of beginning of the rewetting. The second point corresponds to the heat transfer coefficient for the complete wetting, i.e. at the nucleate boiling, and it is determined according to the heat flux of the second type.

The main idea of the proposed method is as follows:

- the wetting rate does not depend on the rate of the fluid supplied from the outside; it depends only on the rate of the steam bubble generation, since under these conditions a free access of the fluid to the steam film is provided;
- the presence of axial – radial heat leakages through cold end elements of the fuel rod leads to the generation of wetting waves at the top and bottom boundaries of the heated section of the fuel rod; and boundaries of wetting waves gradually move to the fuel rod center.

In other words, axial heat leakages into unheated parts of the fuel rod lead to a decrease in the cladding temperature in axial segments near unheated parts of the fuel rod. Thus, rewetting fronts occur and move from upper and lower parts of the fuel rod to the center of the heated length.

The solution of the two-dimensional non-stationary equation of the heat conductivity in the solid with internal heat sources formed the basis of the method:

$$\rho c_p \frac{\partial T}{\partial t} = \frac{\partial}{\partial z} \left(\lambda \frac{\partial T}{\partial z} \right) + \frac{1}{r} \frac{\partial}{\partial r} \left(r \lambda \frac{\partial T}{\partial r} \right) + q_v,$$

where ρ = clad density (kg/m^3);

c_p = clad specific heat (J/kg K);

T = Temperature (K);

λ = clad thermal conductivity (W/m K);

q_v = volume internal heat source (W/m^3).

In this case, ρ , c_p , λ_z , λ_r are functions of the temperature. Additionally, an axial profile of cladding temperature is specified in the region of the rewetting front by the corresponding equations. This profile depends on the velocity of the rewetting front. At the rewetting front the cladding temperature is equal to the minimum stable film boiling temperature. The solution of this equation is reduced to the solution of a system of algebraic equations with respect to the dislocation velocity of the rewetting front. The values obtained for the velocities of the rewetting fronts, moving upward and downward, are used to obtain the moment of rewetting for each axial slice. Distances, covered by each of the rewetting fronts by the time t , are found by integration:

$$L_U(t) = \int_{t_o^U}^t u_U(\tau) d\tau, \quad L_D(t) = \int_{t_o^D}^t u_D(\tau) d\tau,$$

where t = current time (s);

$L_U(t)$ = Distance covered by the rewetting front, moving upward (m);

$L_D(t)$ = Distance covered by the rewetting front, moving downward (m);

t_o^D = time at which rewetting of the lower heated part of the fuel rod starts (s);

t_o^U = time at which rewetting of the upper heated part of the fuel rod starts (s);

$u_U(\tau)$ = Velocity of the rewetting front, moving upward (m/s);

$u_D(\tau)$ = Velocity of the rewetting front, moving downward (m/s).

Model for the rewetting is realized as the separate REWETT subroutine called by QDOT subroutine in the block analyzing heat transfer in the HTRC subroutine (Appendix A).

3. THERMAL MECHANICS

3.1. Accounting for the fuel gas swelling when analyzing fuel-cladding gap size

Deformation of the fuel pellet is determined with only fuel temperature expansion and potential cracking of the fuel (if the cracking option is specified in the input deck) in FRAP-T6 Ver.21. Additional possibility has been introduced to account for the fuel pellet deformation component caused by the fuel gas swelling when analyzing the fuel-cladding gap size.

GRASF subroutine performs calculation of gas release from fuel matrix, and of the relatively volumetric swelling of the pellet. Considering isotropic expansion of the fuel pellet, relative radial displacement of fuel can be presented as:

$$\frac{\Delta r}{r} = \left(\frac{\Delta V}{3V} \right),$$

where r = outer fuel radius (m);

V = fuel volume (m^3).

The obtained value of the fuel displacement is transferred through the additionally developed COMMON BLOCK (WWER.H header) to DEFORM subroutine, where the fuel-cladding radial gap is calculated.

3.2. Cladding ballooning model

Local plastic deformation of the cladding is modeled by BALON2 subroutine driven by FRAP-T6 code. BALON2 belongs to a group of codes that allow to calculate the asymmetric cladding deformation in time. For this purpose the assumption on the azimuth non-uniformity of the cladding temperature is used during the initialization of the BALON2 program. In this case, temperature variations significantly affect the value of the circumferential elongation. The effect of the elongation decrease with the increase in the temperature non-uniformity was intensively studied in experiments that simulate LOCA [10, 11]. According to experiments, this effect is a key factor that influence the cladding elongation. Parametric calculations using the FRAP-T6/BALON2 code also demonstrated a significant sensitivity of the circumferential elongation at burst to the azimuth variation of the cladding temperature (see Fig. 3.1).

Verification of the original version of the code against IGR test data indicates that FRAP-T6 code significantly underestimates peak clad residual hoop strain for the ballooning area [1]. Joint analysis of the experimental observations and BALON2 models confirms that azimuth variation of temperature can sufficiently reduce the cladding circumferential elongation at burst.

Two different approaches were used to describe the fuel rod behavior in the air and water coolant. An original approach of the BALON2 to simulate the asymmetric temperature field in air-cooled fuel rods resulted in unrealistic predictions of the cladding deformation at burst. To solve this problem, the BALON2 program was modified as follows. For the determination of cladding dimensions during the ballooning, the assumption on the cladding bending in the axial plane is used, that leads to a relative offset of the fuel pellet and the cladding till the time of the contact. At the time of the contact of the fuel and the cladding a sharp surge of the cladding temperature is predicted in the contact zone. The use of the bending model for fuel rods under consideration would be unjustified. Therefore, this model was disabled during calculations of air-cooled fuel rods.

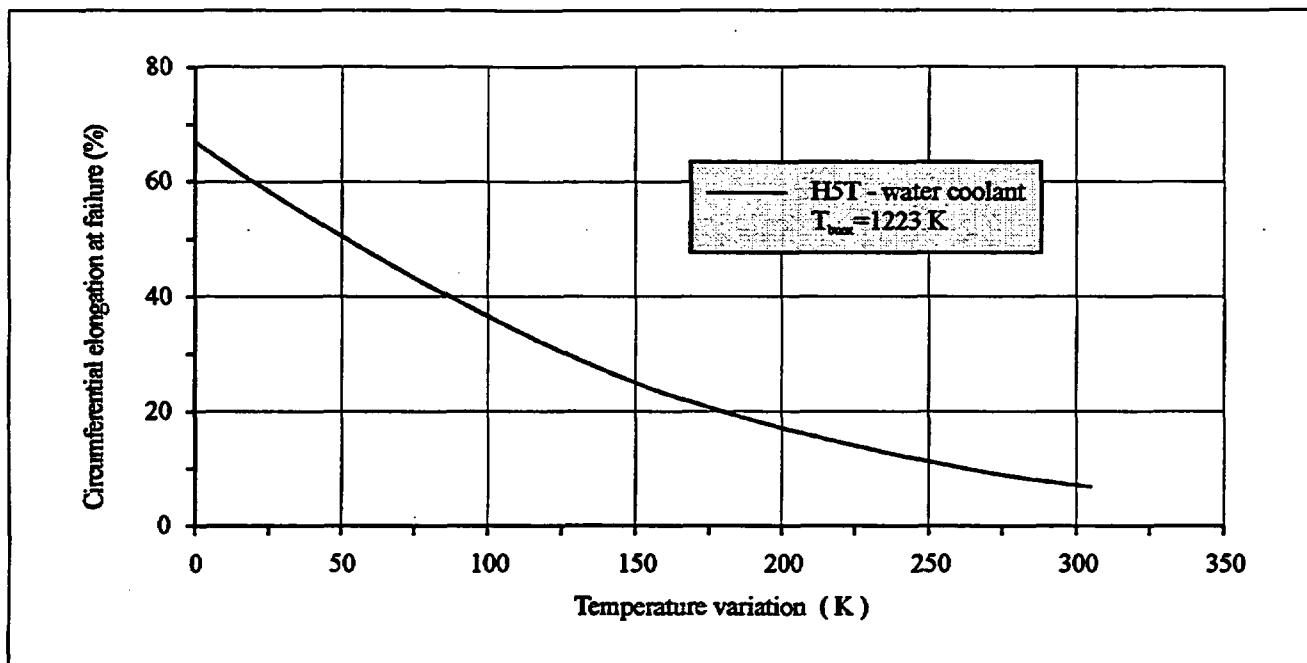


Fig. 3.1. Calculated cladding circumferential elongation at burst vs. azimuth variation of cladding temperature.

On the other hand, the bending model was used in BALON2 calculations for water-cooled fuel rods. It should be noted once more that it was difficult to verify the model since there were no data on the azimuth variation of the temperature. However taking into account the statistic nature of the film boiling and the presence of the geometric eccentricity in the real fuel rod, the prediction of the fuel and cladding contact during the ballooning can be considered as a simplified approach to the simulation of the «hot spot» on the cladding under DNB conditions. In this case modifications were performed for calculations of the gap thermal conductivity at contact (GCONR2 module), called by the BALON2. To prevent unrealistic results when the gap tends to zero, the effective gap thickness was limited by 15 μm .

Correction of the axial length of ballooning region also was made in BALON2 subcode in order to consider specific features of VVER fuel rods. Original version of BALON2 subroutine suggests to consider that axial length is equal to 8 cm. But the heated length of VVER fuel rods is equal to 15 cm only. Use of the axial length of ballooning, which exceeds the half of the fuel rod length, makes it much more difficult to interpret the calculation results. Axial length in the BALON2 was decreased to 3 cm according to the post-test examinations of the VVER fuel rods tested in IGR.

4. FISSION GAS BEHAVIOR

To analyze fission gas release (FGR) in the pulse regime it is necessary to specify initial distribution of the fission gas. Standard procedure of calculating initial concentration of Xe and Kr in the fuel matrix is done with the standard FRAPCON-2 [12] code under the base irradiation conditions. FRAPCON-2 code is interfaced with FRAP-T6 code. The data calculated by FRAPCON-2 code are the input data for FRAP-T6 code i.e. for example, axial and radial distribution of Xe and Kr concentration in the fuel matrix after the base irradiation.

As the developers of FRAP-T6/VVER version did not have a steady-state code for high burnup VVER fuel, which provides the whole data set in the form suitable for FRAP-T6 code, the decision was made to use FRAP-T6 code capabilities to assess fission gas release. Thus, a number of steady-state models of the fuel and cladding deformation versus burnup and power history were incorporated into FRAP-T6 code. It is also possible to specify the change of the power rate radial non-uniformity under base irradiation conditions.

The model of fission gas behavior that realized in the GRASF subroutine calculates the generation of fission gas atoms and their further distribution in the fuel matrix depending on the temperature and burnup. In order to get the input data to analyze fission gas release over the IGR test, the following characteristics are to be calculated by the end of the fuel cycle:

- radial distribution of fission gas concentration in the fuel grains;
- radial distribution of the fission gas concentration on grain surfaces;
- radial distribution of the fission gas concentration at the grain edges.

4.1. Approach to analyze fission gas behavior under base irradiation conditions

It is important to note that FRAP-T6 code was not specially oriented towards analysis of the quasi-steady-state regime of operation of the fuel rods. The existing steady-state models are of auxiliary nature and can be used to analyze pre-transient condition of only fresh fuel rods or the fuel rods of low burnup. To model the pre-transient quasi-steady-state regime it is necessary to account for additional physical processes and effects that determine the state of fuel under deep burnup. Hence, additional models to analyze fuel rod behavior in the mode of the quasi-steady-state thermal loading were incorporated into the code.

4.1.1. Fuel swelling due to accumulation of the fission products

Despite the fact that it is possible to analyze spatial fuel swelling in the model of fission gas release, FRAP-T6 code did not account for the radial fuel displacement due to that effect. In the present version the fuel volumetric swelling converted into the radial displacement is used to identify the fuel-cladding gap size for both steady-state and accident regime. Accounting for the fuel swelling can be performed according to three options:

1. Using GRASF subroutine which is a part of FRAP-T6 code original version.
2. Using FSWELL subroutine from MATPRO-V11.

The model of the steady-state fuel swelling similar to the swelling model in FRAP-S3 code [13] has been included.

3. The option that does not account for the fuel swelling when analyzing gas gap size.

Option (1) is used for practical calculations of fuel swelling in steady-state and accident conditions. The option (2) was included as auxiliary. It is based on MATPRO correlation and used only for comparative

analysis of fuel swelling calculated with the GRASF and MATPRO routines. The option (3) does not take into account the fuel displacement due to fuel swelling as postulated in the original FRAP-T6 manual.

4.1.2. Irradiation-induced fuel densification

The model of additional fuel densification due to irradiation from MATPRO-V11 [5] package (FUDENS subroutine) has been included into DEFORM subroutine. The incorporated correlation allows to account for the decrease of the fuel diameter during the initial stage of burnup due to sintering of pores with the diameter less than 1 μm .

4.1.3. Dependence of the power rate radial non-uniformity versus time

As the input data FRAP-T6 code foresees specification of only power rate radial non-uniformity, constant with time. For the quasi-steady-state calculations it is necessary to account for the change of the power rate radial non-uniformity. The possibility to model variable in time radial coefficient of the power rate non-uniformity has been added to the code. This coefficient allows to consider change of the power rate radial profile (burnup) according to the data of neutronic calculations. To realize this RIMTIM, FINT and RIMMOD subroutines have been introduced. These subroutines perform interpolation of the earlier specified 3D data file depending on the fuel radius at every time moment. 3D data file is the dependence of the specified power rate non-uniformity coefficient along the fuel radius and burnup. Appendix A presents the texts of RIMTIM, FINT and RIMMOD subroutines.

4.2. Initial data and the procedure to analyze fission gas behavior under the base-conditions

4.2.1. Extension of the power history array

For more accurate specification of the input data describing power history, that includes both base irradiation conditions and transient heat-up, the array contained time dependence of power rate (PTHA) was extended from (100,1) to (1200,1)

4.2.2. The method to specify input data for the analysis of base irradiation

The following set of the input data (graphically presented in Fig. 4.1) is proposed to analyze pre-transient distribution of fission gas in the fuel.

4.2.3. Analysis of the fuel rod behavior under base irradiation conditions

The fuel rod power history is specified according to the data of neutronic calculations. In particular, this was done to analyze the behavior of VVER fuel rods tested in IGR reactor. To model the behavior of fuel rods in the quasi-steady-state operation regime the height of the fuel rod active part was divided into the sections approximately corresponding to the length of re-fabricated samples of fuel rods. Then thermal-mechanical analysis of the fuel rod behavior was performed with FRAP-T6 code for the base irradiation conditions up till the set burnup ($\sim 50 \text{ MWd/kg U}$). Input data on the state of fuel in the pre-transient moment ($t=0$) are the results of this analysis. At the time moment $t=0$ the code foresees replacement of the following fuel rod parameters in accordance with the data base for IGR tests of the VVER fuel rods:

1. Fuel rod geometric dimensions
2. Internal gas pressure in fuel rod

3. Composition of the filling gas

4. Capsule cooling conditions

Then the calculation of fuel rod behavior under transient condition is started up.

The proposed method to analyze fission gas release under the base irradiation conditions with FRAP-T6 code should only be considered as the method allowing to quantitatively evaluate amount of gas in the fuel matrix, and to download the initial spatial distribution of the fission gas. This method does not claim for the detailed thermal-mechanical analysis of the fuel rod under base irradiation conditions, which is to be performed with the codes of FRAPCON-(2,3) [12, 14], TRANSURANUS [15] type.

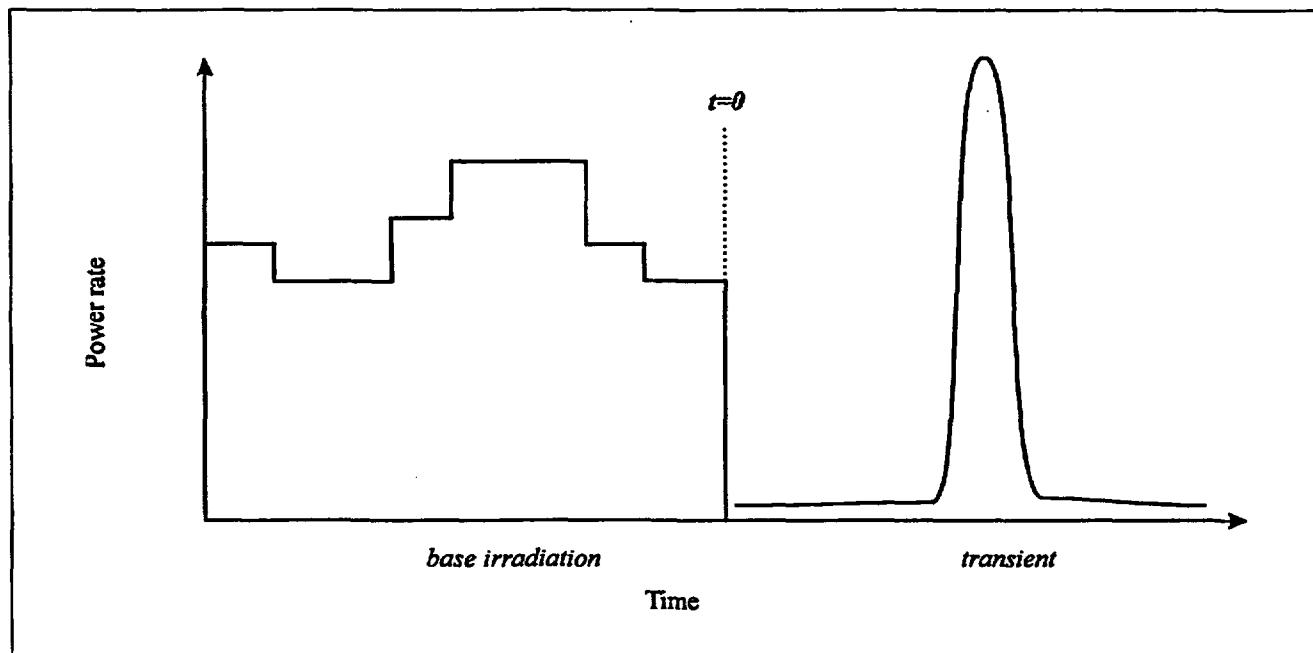


Fig. 4.1. Interpretation of the power history specification under base irradiation and transient conditions for FRAP-T6/VVER code.

5. ALTERNATIVE THERMAL - PHYSICAL MATERIAL PROPERTIES (MATPRO-V11 LIBRARY EXTENSION)

We present the choice and justification of the models of the main thermal-physical and mechanical properties of Zr-1%Nb cladding and UO₂ fuel in order to adapt FRAP-T6 code for modeling fuel rod behavior under the pulse testing conditions in IGR reactor.

Correlations of physical and mechanical properties of Zr-1%Nb alloy and the Russian type of fuel were added to the MATPRO-V11 package. Addition to the package of MATPRO-V11 material properties was done in the following subroutines:

Fuel

1. FTHCON - Thermal conductivity vs. temperature and burnup
(additional subroutines: TCOR, BURNUP)
2. FTHEXP - Thermal expansion
3. FCP - Specific heat
4. FENTHL - Enthalpy
5. PHYPRP - Thermal-physical constants

Cladding

1. CTHCON - Thermal conductivity
2. CCP - Specific heat
3. CCPINT - Enthalpy
4. CTHEXP - Thermal expansion
5. CMHARD - Micro-hardness
6. CELMOD - Young's modulus
7. EMCPIR - Poisson's ratio
8. CKMN - Strength coefficient, strain hardening exponent, strain rate sensitivity exponent vs. temperature and strain rate for fresh and irradiated cladding
9. CMLIMT - Ultimate mechanical parameters
10. COBILD - High-temperature oxidation
11. PHYPRP - Thermal-physical constants

FORTRAN texts of the respective subroutines were prepared in the format of MATPRO-V11 library package and are fully presented in Appendix A.

5.1. Thermal-physical properties of fuel

5.1.1. Fuel specific heat (FCP) and enthalpy (FENTHL)

Table 5.1 and Fig. 5.1 present the dependence of fuel specific heat versus temperature. Fuel enthalpy is obtained by integrating specific heat dependence for the temperature on condition that enthalpy at 20°C is equal to zero.

Table 5.1. Dependence of fuel specific heat and enthalpy on temperature [16].

Parameter	Temperature (K)														
	293	500	700	900	1100	1300	1500	1700	1900	2100	2300	2500	2700	2900	3100
Specific heat (J/kg K)	280	287	302	310	314	319	320	328	340	364	390	426	470	520	594
Enthalpy (kJ/kg)	0	57.6	116.5	177.7	240.1	303.4	367.3	432.1	498.9	569.3	644.7	726.3	815.9	914.9	1026

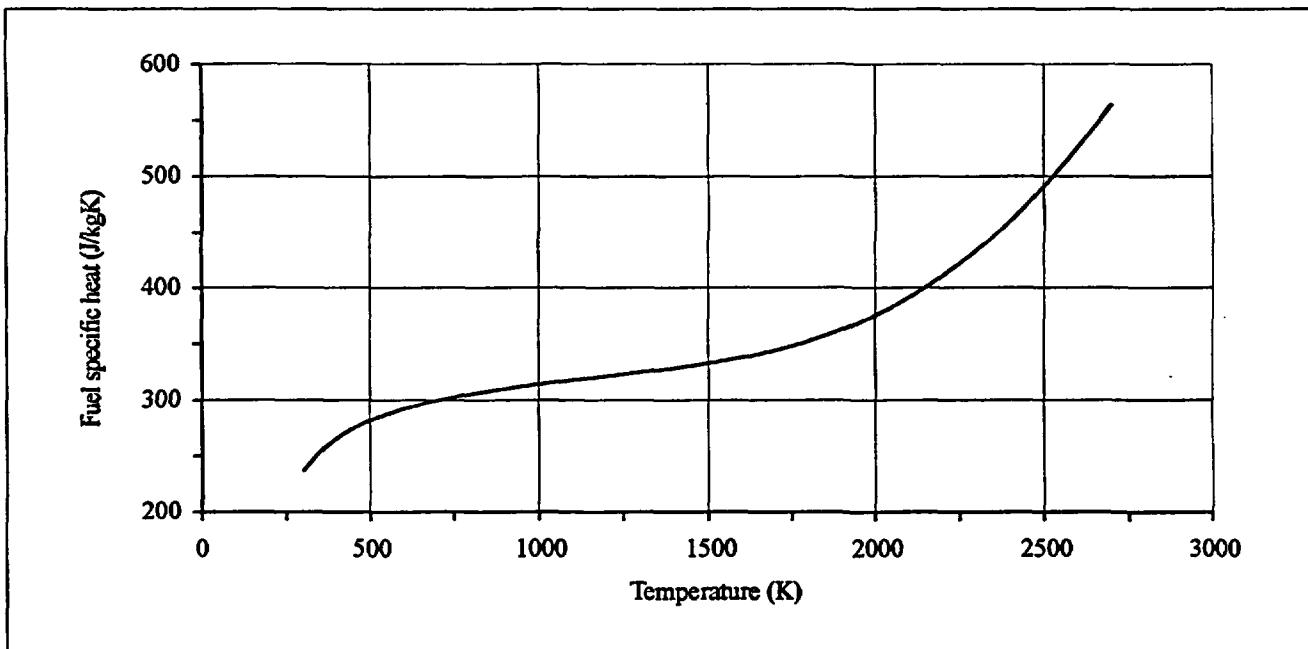


Fig. 5.1. VVER fuel specific heat vs. temperature.

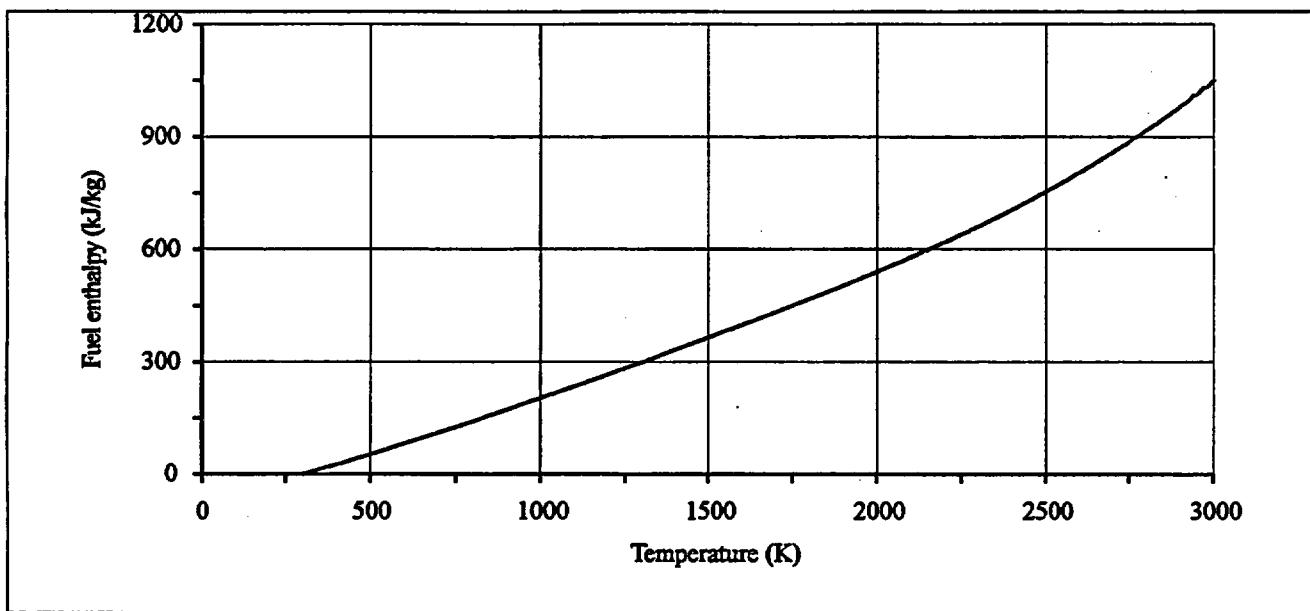


Fig. 5.2. VVER fuel enthalpy vs. temperature.

5.1.2. Thermal expansion (*FTHEXP*)

Table 5.2 and Fig. 5.3 present the temperature dependent correlation of thermal expansion for fresh VVER fuel.

Table 5.2. Thermal expansion of VVER fresh fuel (%) vs. temperature [16].

Temperature (K)	Linear expansion (%)
293	0.0000
400	0.077
600	0.240
800	0.451
1000	0.678
1200	0.922
1400	1.182
1600	1.458
1800	1.751
2000	2.060
2200	2.385
2400	2.727
2600	3.085
2800	3.4600
3000	3.851
3080	4.012

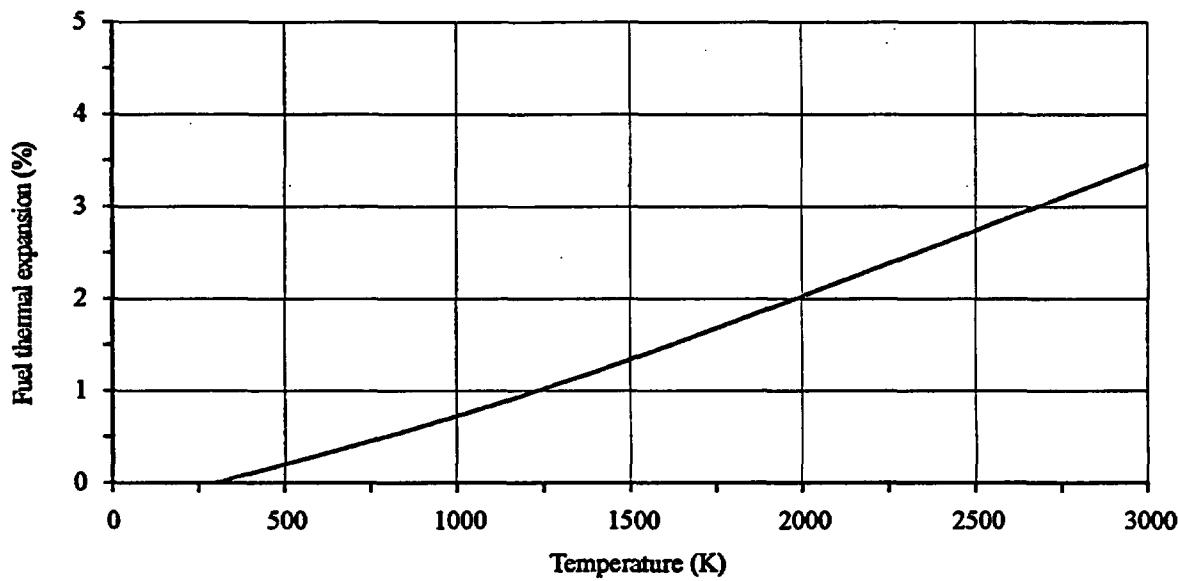


Fig. 5.3. Fresh fuel thermal expansion vs. temperature for VVER-type fuel [16].

5.1.3. Thermal conductivity of the VVER type of UO_2 , and dependence of thermal conductivity versus fuel burnup (FTHCON, BURNUP, TCOR)

Fresh fuel thermal conductivity coefficient is determined according to the correlation [17]:

$$\lambda_0 = 2.158 \lambda_{0.95} \rho / (32.91 - \rho),$$

where λ_0 = fresh fuel thermal conductivity (W/m K);

$\lambda_{0.95}$ = thermal conductivity of fuel with 95 % of theoretical density (W/m K);

ρ = fuel density (g/cm^3).

Thermal conductivity coefficient of the fuel with the density of 95% of the theoretical density is determined according to the correlation [17]:

$$\lambda_{0.95} = 100 / (0.0258 \cdot T + 3.77) + 1.1 \cdot 10^{-4} \cdot T + 1.01 \cdot 10^{-11} \cdot T^3 \cdot \exp(7.2 \cdot 10^{-4} \cdot T),$$

where T = temperature (K).

Thermal conductivity of the burnup fuel is determined according to the dependencies [18, 19]:

$$\lambda_B = \lambda_0 K_1 K_2,$$

where λ_B = burnup fuel thermal conductivity (W/m K);

λ_0 = fresh fuel thermal conductivity (W/m K);

K_1 and K_2 = empirical coefficients.

Dimensionless K_1 and K_2 coefficient are determined as follows [18, 19]:

$$K_1 = (0.053 + 2.2 \cdot 10^{-4} \cdot T) / (0.053 + 0.00171 \cdot b + (2.2 - 0.000533 \cdot b) \cdot 10^{-4} \cdot T),$$

$$K_2 = 1 - 0.001 \cdot c \cdot b,$$

$$c = 5.31 - 3.42 \cdot 10^{-3} \cdot T + 0.4 \cdot 10^{-6} \cdot T^2 \text{ for } T < 1773,$$

$$c = 0.5 \text{ for } T > 1773,$$

where b = burnup (MWd/kg U);

T = temperature (K).

Fig. 5.4 presents dependencies of thermal conductivity coefficient of the VVER fuel type versus temperature for the fresh fuel and fuel with the burnup of 30 and 60 MWd/kg U. Appendix A presents the text of FCON subroutine that performs selection of the option to calculate fuel thermal conductivity. Dependencies for thermal conductivity of the VVER fuel are included into TCOR subroutine-function. BURNUP subroutine contains dependencies of thermal conductivity versus burnup. Texts of these subroutines are presented in Appendix A.

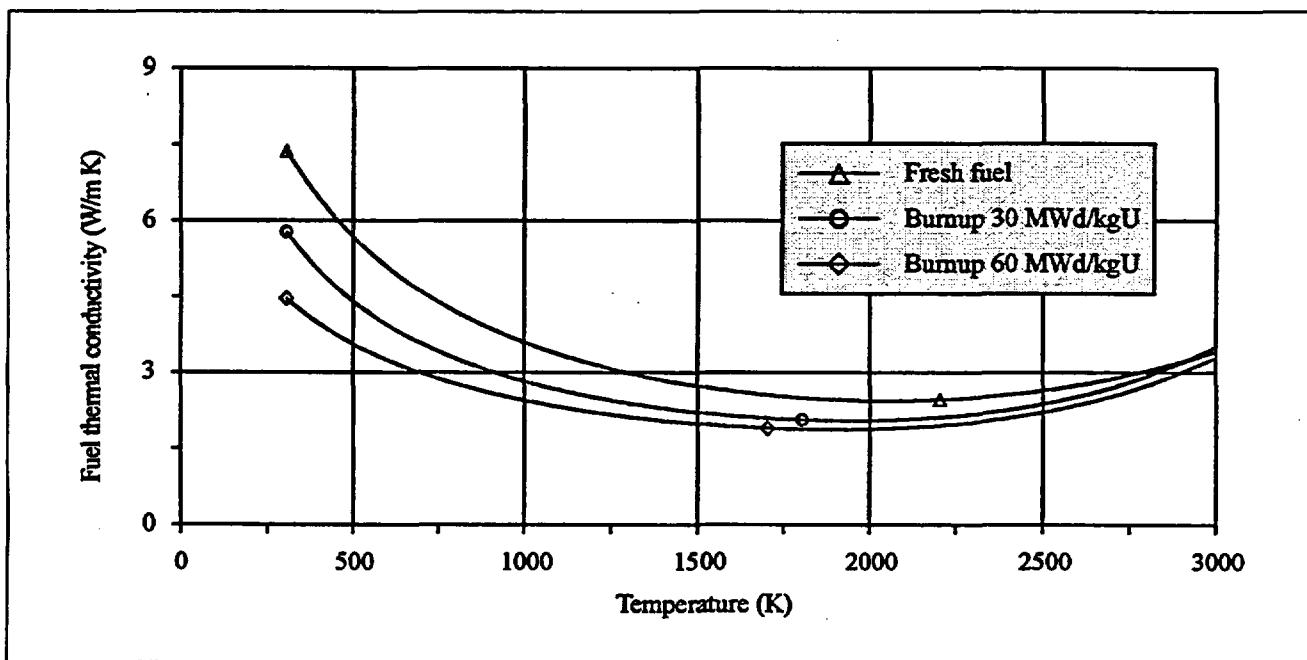


Fig. 5.4. VVER fuel thermal conductivity vs. temperature.

5.1.4. Thermal-physical constants (PHYPRP)

Thermal-physical constants of the VVER fuel are presented in Table 5.3.

Table 5.3. Thermal-physical constants of VVER fuel.

Material	Stoichiometric UO_2
Melting temperature (K)	$3111 - 3.577 \cdot B$, where B - burnup (MWd/kg U)
Heat of fusion (J/g)	269
Theoretical density (kg/m^3)	10970

5.2. Thermal-physical properties of Zr-1%Nb cladding

5.2.1. Thermal-physical constants (PHYPRP)

Thermal-physical constants of the Zr-1%Nb cladding alloy in accordance with [20] are presented in Table 5.4.

Table 5.4. Thermal-physical constants of Zr-1%Nb alloy.

Material	Zr-1%Nb
Melting temperature (K)	2133
Fusion heat (J/g)	210
Beginning of α - β transition (K)	883
End of α - β transition (K)	1153
Density (kg/m ³)	6550

5.2.2. Specific heat (CCP) and enthalpy (CCINP)

Table 5.5 and Fig. 5.5 present the dependence of the unirradiated cladding specific heat and enthalpy versus temperature [21]. Cladding enthalpy is obtained by integrating specific heat dependence for the temperature on condition that enthalpy at 20°C is equal to zero. The obtained dependence is presented in Table 5.5 and in Fig. 5.5.

Table 5.5. Dependence of Zr-1%Nb specific heat and enthalpy on temperature.

Parameter	Temperature (K)														
	393	473	573	673	773	873	883	973	1025	1073	1153	1173	1200	1300	1400
Specific heat (J/kg K)	345	360	370	380	383	385	448	680	816	770	400	392	392	393	393
Enthalpy (kJ/kg)	34.1	61.9	97.5	134	171	209	214	262	301	339	385	393	402	445	485

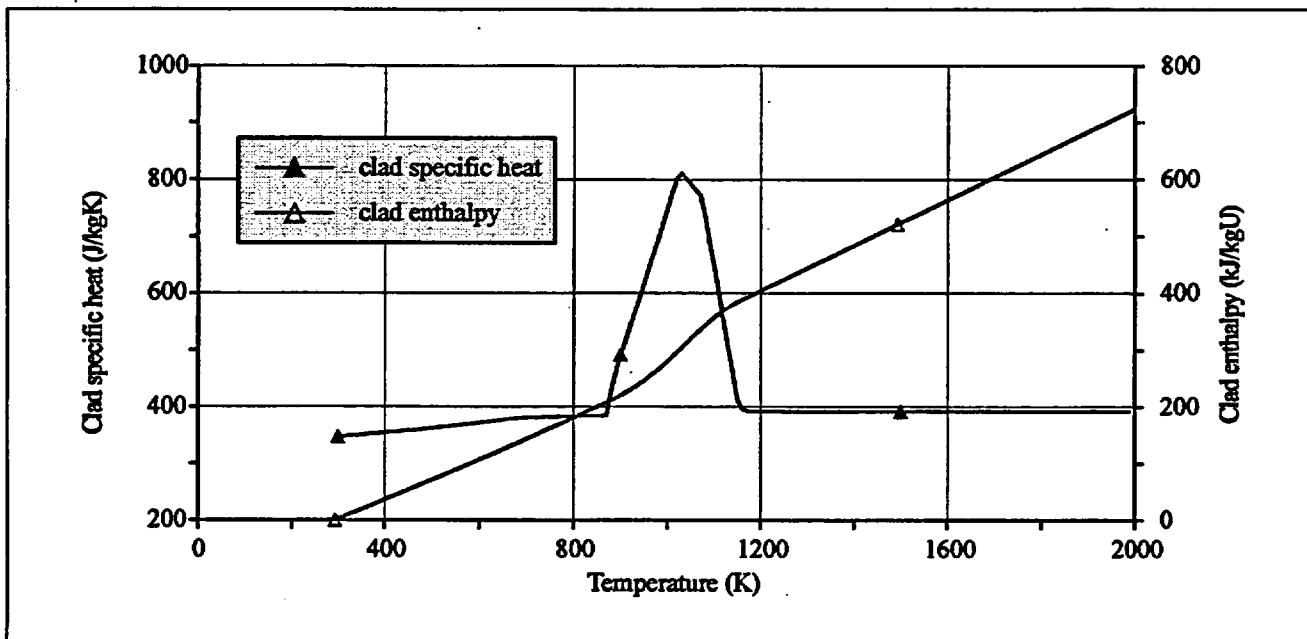


Fig. 5.5. Zr-1%Nb clad specific heat and enthalpy vs. temperature.

Appendix A presents the text of CCP and CCPINT subroutines where selection of options is performed to calculate specific heat and enthalpy. Cladding enthalpy is obtained by integrating specific heat for the temperature.

5.2.3. Thermal expansion (CTHEXP)

Anisotropic model of the Zr-alloy cladding thermal expansion has been approved for the MATPRO-V11 package. Table 5.6 presents respective dependencies to determine thermal expansion factor up to the temperature of 923 K [22].

Table 5.6. Thermal expansion coefficients in hoop and axial directions for Zr-1%Nb cladding.

Parameter	Temperature (K)							
	293 – 393		393 – 573		573–773		773 – 923	
	α_e	α_z	α_e	α_z	α_e	α_z	α_e	α_z
Thermal expansion coefficients (1/K)	$5.7 \cdot 10^{-6}$	$5.3 \cdot 10^{-6}$	$5.9 \cdot 10^{-6}$	$5.4 \cdot 10^{-6}$	$6.3 \cdot 10^{-6}$	$5.5 \cdot 10^{-6}$	$6.8 \cdot 10^{-6}$	$5.6 \cdot 10^{-6}$

The correlations presented in Table 5.7 were used to determine thermal expansion of Zr-1%Nb alloy at the temperatures higher than 923 K. Dependencies were obtained on the basis of extrapolation of the data presented in Table 5.7; it was assumed that general view of the dependence for thermal expansion of Zr-1%Nb alloy was equidistant to the dependence for Zry alloy.

Table 5.7. Temperature dependence of hoop (ε_θ) and axial (ε_z) components of thermal expansion of Zr-1%Nb alloy for temperature above 923 K.

Temperature (K)	Thermal expansion of Zr-1%Nb alloy (%)
923 - 1153	$\varepsilon_\theta = -17.95 + 0.0549 T - 5.4 \cdot 10^{-5} T^2 + 1.74 \cdot 10^{-8} T^3$ $\varepsilon_z = -17.28 + 0.0533 T - 5.3 \cdot 10^{-5} T^2 + 1.72 \cdot 10^{-8} T^3$
above 1153	$\varepsilon_\theta = -0.886 + 9.7 \cdot 10^{-4} T$ $\varepsilon_z = -1.038 + 9.7 \cdot 10^{-4} T$

Fig. 5.6 and Fig. 5.7 present the dependence of thermal expansion versus temperature for the cladding of Zr-1%Nb alloy in the radial and axial directions. This block of correlations has been incorporated into CTHCON subroutine (Appendix A).

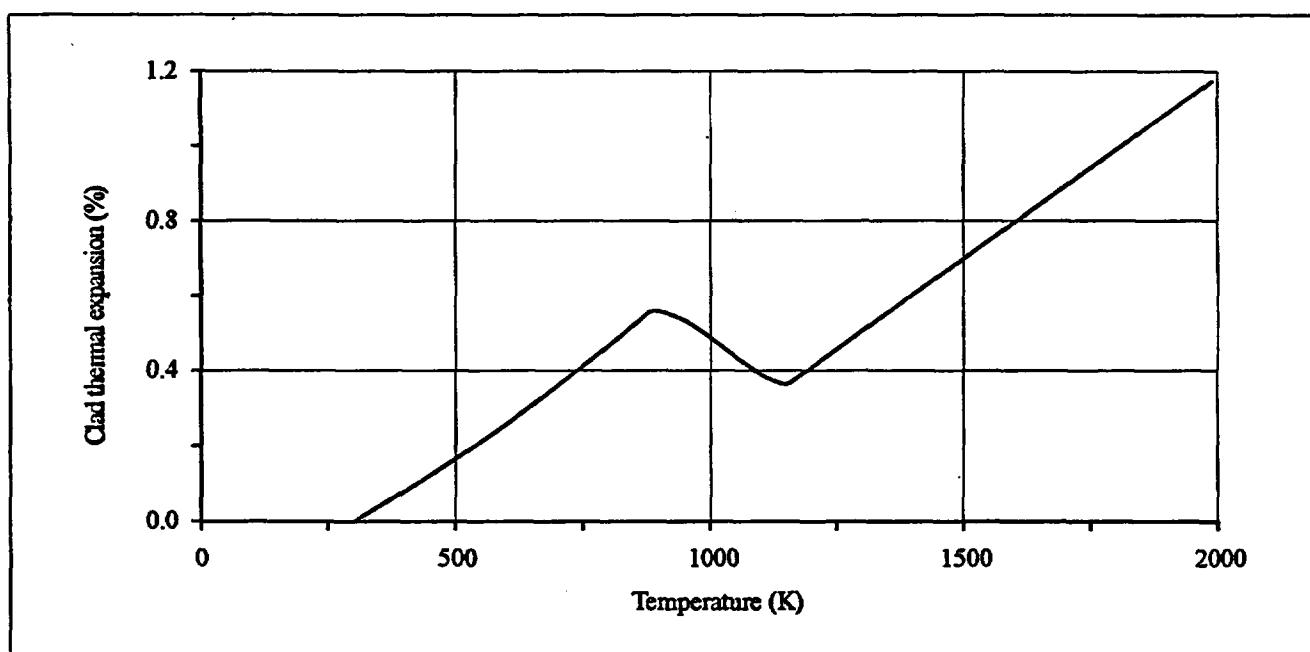


Fig. 5.6. Hoop component of Zr-1%Nb clad thermal expansion vs. temperature.

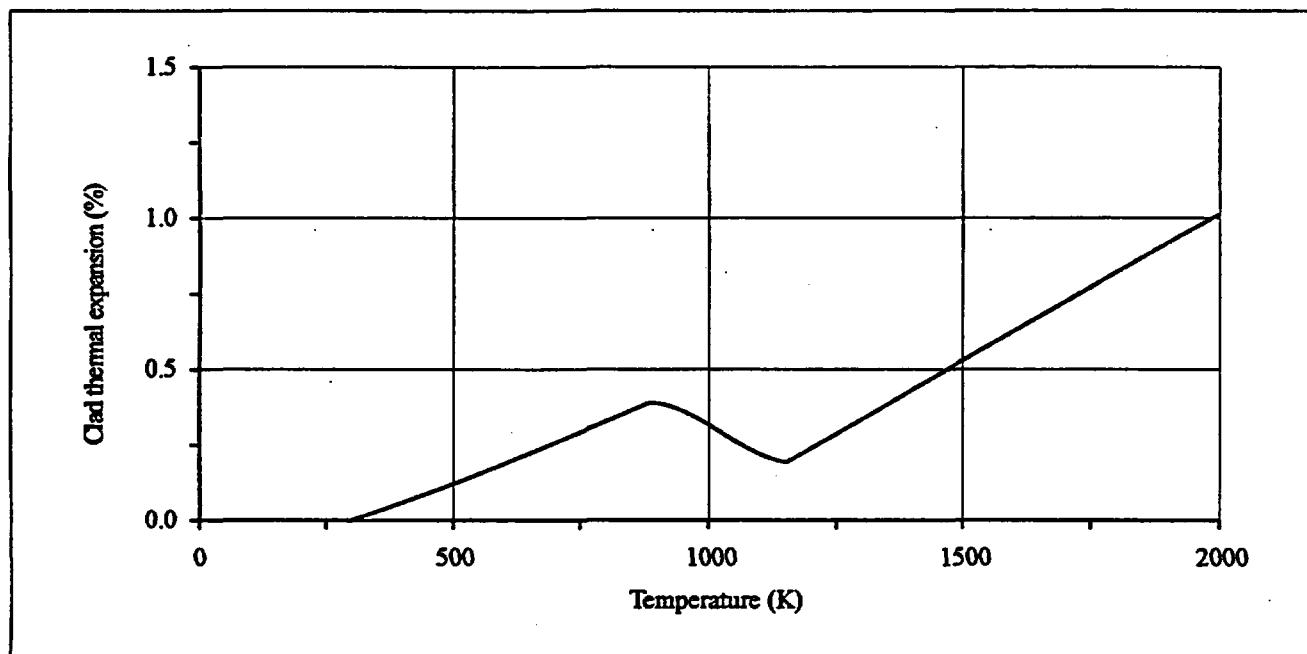


Fig. 5.7. Axial component of Zr-1%Nb clad thermal expansion vs. temperature.

5.2.4. Thermal conductivity (CTHCON)

Thermal conductivity of the cladding material made of Zr-1%Nb alloy was obtained by approximation and extrapolation of experimental results [20, 22]. Following analytical equation is defined by the formula:

$$\lambda = 15.0636 \exp (0.4618 \cdot 10^3 T),$$

where λ = thermal conductivity (W/m K);

T = temperature (K).

Table 5.8 and Fig. 5.8 present the dependence of the cladding thermal conductivity versus temperature.

Table 5.8. Dependence of Zr-1%Nb thermal conductivity on temperature.

Parameter	Temperature (K)									
	300	500	700	900	1100	1300	1500	1700	1900	2000
Thermal conductivity (W/m K)	17.31	18.99	20.82	22.84	25.05	27.47	30.13	33.05	36.25	37.96

Appendix A presents the text of CTHCON subroutine which perform selection of the option to calculate thermal conductivity of the cladding material.

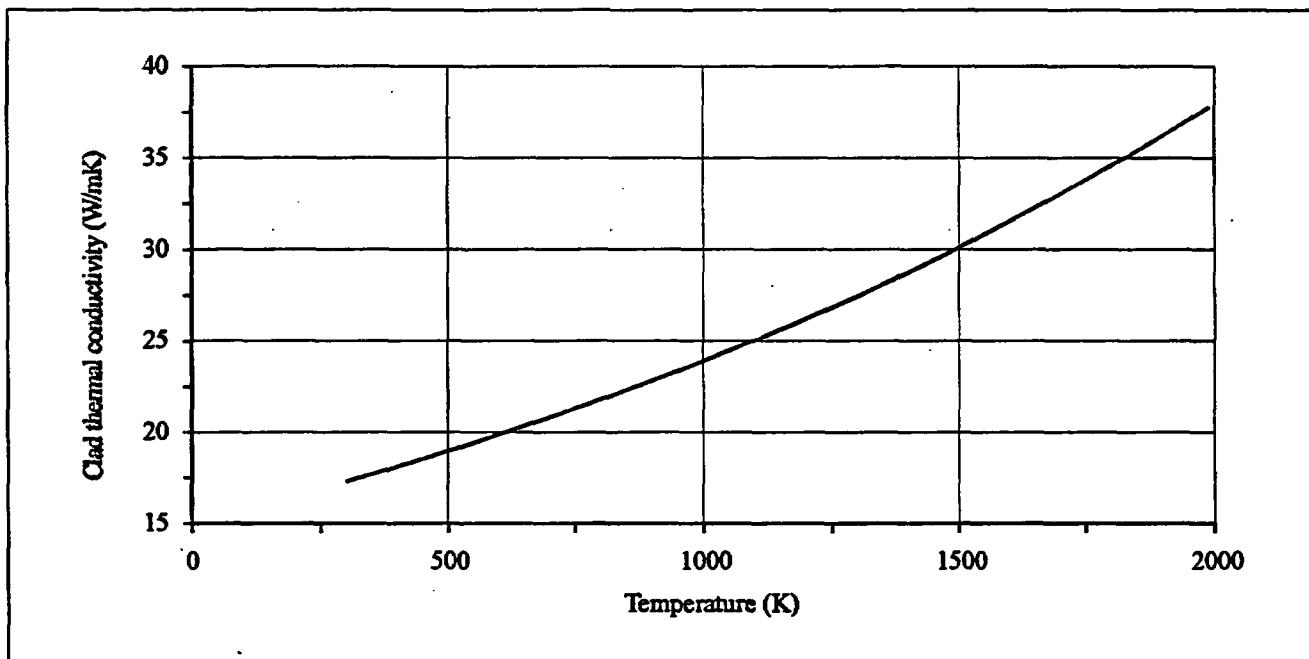


Fig. 5.8. Dependence of Zr-1%Nb thermal conductivity on temperature.

5.2.5. High temperature oxidation (COBILD)

MATPRO-V11 package uses the model of parabolic kinetics to describe the process of the cladding oxidation in the steam and water coolant:

$$W^2 = K_p(T) \cdot \tau,$$

where $W = \alpha\text{-Zr}(0)$ oxide layer thickness (m);

K_p = proportional factor (determined separately for ZrO_2 and $\alpha\text{-Zr}(0)$) (m^2/s);

τ = time (s).

Proportion constant is the function of temperature and is described by the Arrhenius formula:

$$K_p(T) = A \cdot \exp(-B/T),$$

where T = temperature (K);

A, B = factors characterizing zirconium alloy oxidation.

Constants A and B existing in the MATPRO-V11 package were supplemented with the data on high temperature oxidation of Zr-1%Nb and Zry alloys, obtained for the atmospheric pressure [23, 5] (see Table 5.9).

Table 5.9. Arrhenius formula coefficients for K_p constant [23, 5].

Alloy	Temperature region (K)	A	B
Zry	<1853	$2.252 \cdot 10^{-6}$	18063
Zry	>1853	$2.07 \cdot 10^{-6}$	16014
Zr-1%Nb	<1773	$5.19 \cdot 10^{-7}$	15355
Zr-1%Nb	>1773	$17.72 \cdot 10^{-7}$	14680

Specific energy of the metal-water reaction for Zr-1%Nb alloy is assumed to be 6.49 kJ/g [23]. COBILD subroutine is supplemented with the coefficients for the parabolic kinetics of Zr-1%Nb alloy oxidation.

5.3. Mechanical properties of Zr-1%Nb cladding

5.3.1. Young's modulus (CELMOD) and Poisson's ratio (EMCPIR)

Correlation for calculating Young's modulus of Zr-1%Nb alloy is presented with the following two expressions [20]:

$$273 \text{ K} < T \leq 1073 \text{ K}$$

$$E = 1.121 \cdot 10^{11} - 6.438 \cdot 10^7 \cdot T,$$

$$1073 \text{ K} < T \leq 1273 \text{ K}$$

$$E = 9.129 \cdot 10^{10} - 4.500 \cdot 10^7 \cdot T,$$

where T = temperature (K);

E = elastic modulus (Pa).

Fig. 5.9 presents the dependence of the Young's modulus for Zr-1%Nb.

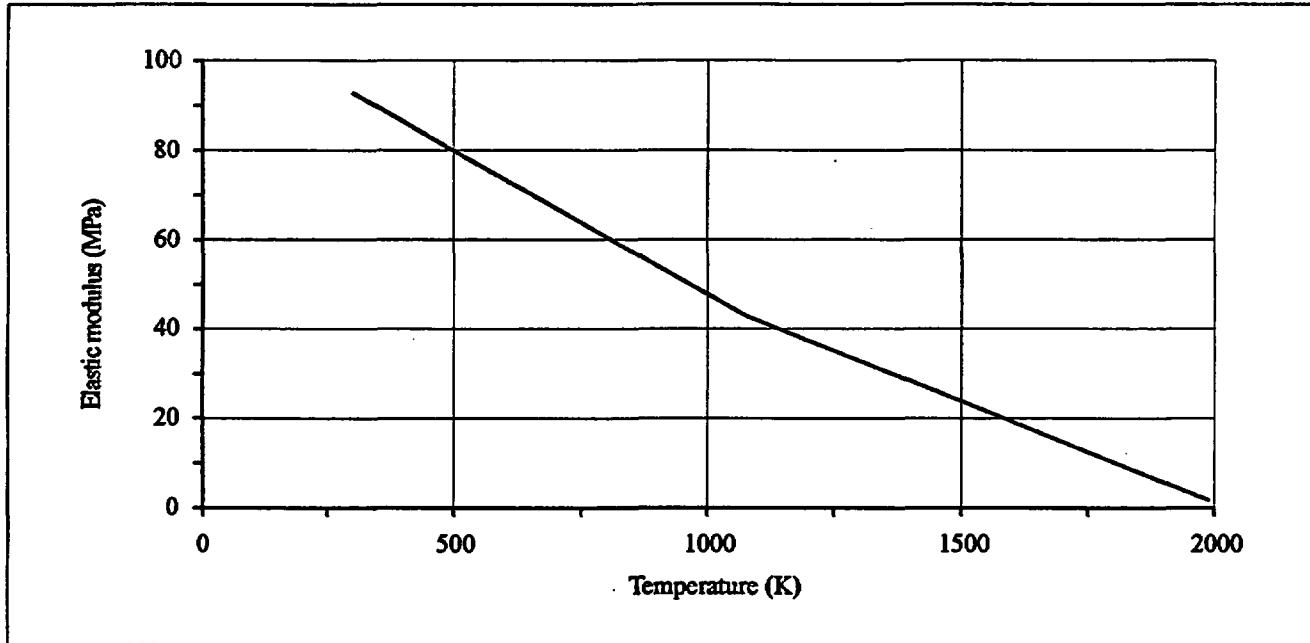


Fig. 5.9. Dependence of Young's modulus of Zr-1%Nb on temperature.

The data on the dependence of the Young's modulus versus temperature are incorporated into CELMOD subroutine.

Experimental data on the Poisson's ratio for Zr-1%Nb are approximated by the following expression [20]:

$$\mu = 0.42628 - 5.556 \times 10^{-5} T,$$

where T = temperature (K).

Dependence of the Poisson's ratio is incorporated into EMCPIR subroutine.

Appendix A presents the texts of CELMOD and EMCPIR subroutines which perform selection of options to calculate the respective properties.

5.3.2. Meyer micro-hardness (CMHARD)

Cladding micro-hardness according to Meyer is used to analyze the contact component of the fuel-cladding gap thermal conductivity. Micro-hardness of Zr-1%Nb corresponds approximately to three times value of the yield stress [22]. The values of the cladding micro-hardness are presented in the Table 5.10 versus temperatures from 293 to 773 K according to [22].

Table 5.10. Meyer hardness data for Zr-1%Nb alloy

T (K)	293	373	473	573	673	773
Yield stress (MPa)	230	200	180	161	140	120
Micro-hardness (MPa)	690	600	540	483	420	360

Analytical curve for micro-hardness of Zr-1%Nb alloy based on the data presented in Table 5.10, can be described by the following formula:

For $298 < T < 773$ K

$$H = 2172.1 - 10.7055 \cdot T + 0.02765 \cdot T^2 - 3.278 \cdot 10^{-5} \cdot T^3 + 1.423 \cdot 10^{-8} \cdot T^4,$$

where T = temperature (K).

The following linear extrapolation of the data for the temperature range higher than 773 K has been accepted due to the lack of data on the micro-hardness of Zr-1%Nb alloy:

$$H=850.0 - 64.0 T, \quad \text{assuming if } H < 0.1 \text{ MPa, else } H=0.1 \text{ MPa.}$$

The option for selection of the Meyer micro-hardness correlation for Zr-1%Nb alloy is realized in CMHARD subroutine.

5.3.3. Plastic deformation of the cladding (CKMN)

MATPRO-V11 [5] package uses the following basic equation to describe the correlation between the stress and strain depending on the loading conditions and the state of the cladding material:

$$\sigma = K \varepsilon^n \left(\frac{\varepsilon}{\varepsilon_0} \right)^m,$$

where σ = true effective stress (MPa);

K = strength coefficient (MPa);

ε = true effective strain (per-unit);

n = strain hardening exponent (per-unit);

$\dot{\varepsilon}$ = current strain rate (1/s);

ε_0 = basic strain rate (1/s);

m = strain rate sensitivity exponent (per-unit).

In framework of the experimental program to measure the mechanical properties of unirradiated and irradiated (-50 MWd/kg U) Zr-1%Nb cladding the analytical correlations for K , n , m were obtained [1].

The values of strength coefficient and strain hardening exponent as function of temperature for two burnup levels (0 and 50 MWd/kg U) are presented in Fig. 5.10, Fig. 5.11 and in Table 5.11.

Table 5.11. Correlations to calculate strength coefficient and strain hardening exponent vs. temperature for Zr-1%Nb cladding.

Parameter	Type of cladding	
	unirradiated	irradiated
Strength coefficient (MPa)	$293 < T \leq 795.18 \text{ K}$ $K = 863.33 - 1.90882 T + 0.00209374 T^2 - 9.91178 \cdot 10^{-7} T^3$	$293 < T \leq 749.45 \text{ K}$ $K = 738.221 + 0.0395682 T - 0.00100875 T^2 + 0.370178 \cdot 10^{-6} T^3$ $749.45 < T \leq 846.44 \text{ K}$ $K = 8.34707 \cdot 10^5 \exp(-0.01035 T)$
	$795.18 < T \leq 926.62 \text{ K}$ $K = 1.08414 \cdot 10^4 \exp(-0.00521825 T)$	$846.44 < T \leq 926.62 \text{ K}$ $926.62 < T \leq 1123.54 \text{ K}$ $K = 396.363 - 0.334806 T$ $T > 1123.54 \text{ K}$ $K = 56.6424 - 0.0324407 T$
Strain hardening exponent (per-unit)	$293 < T \leq 1223 \text{ K}$ $n = 0.0462842 + 0.000197952 T - 0.331487 \cdot 10^{-6} T^2 + 1.39133 \cdot 10^{-10} T^3$	$293 < T \leq 752.37 \text{ K}$ $n = 0.0054616 + 3.12237 \cdot 10^{-4} T - 0.668358 \cdot 10^{-6} T^2 + 0.430236 \cdot 10^{-9} T^3$ $752.37 < T \leq 854.72 \text{ K}$ $n = -1.58974 + 0.00500594 T - 4.99134 \cdot 10^{-6} T^2 + 1.62978 \cdot 10^{-9} T^3$ $T > 854.72 \text{ K}$ $n = 0.047$

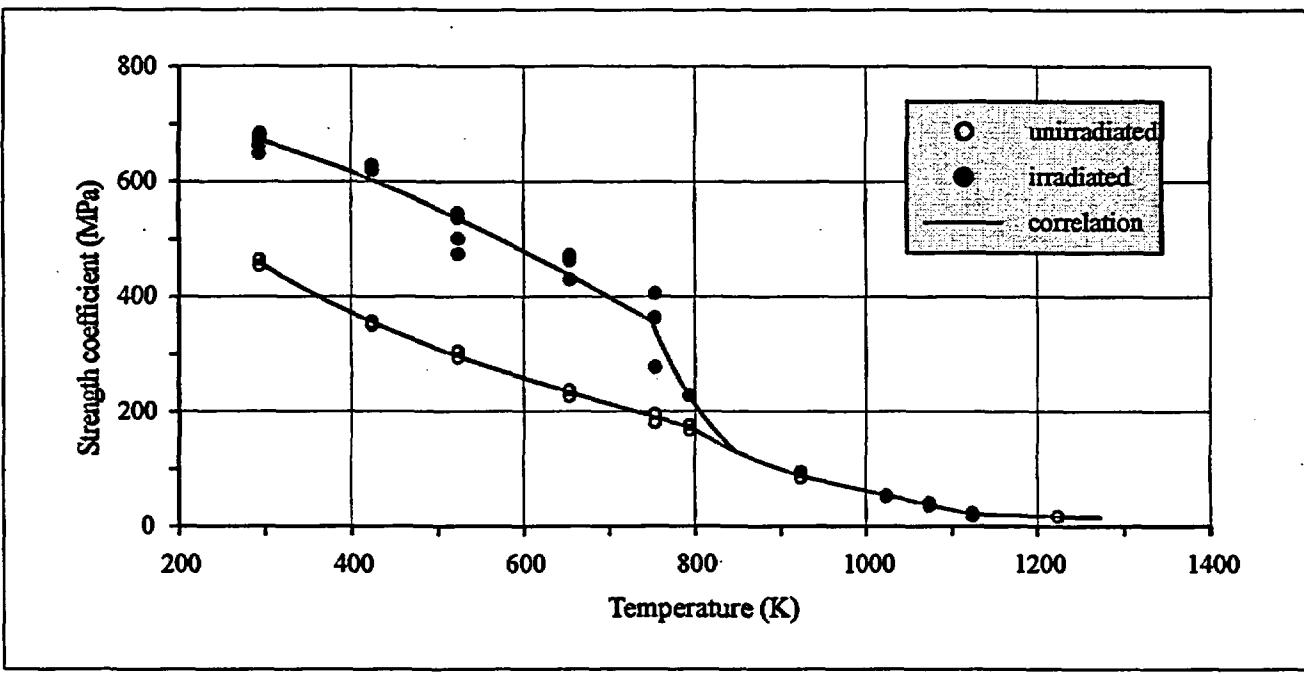


Fig. 5.10. Strength coefficient vs. temperature for unirradiated and irradiated Zr-1%Nb cladding.

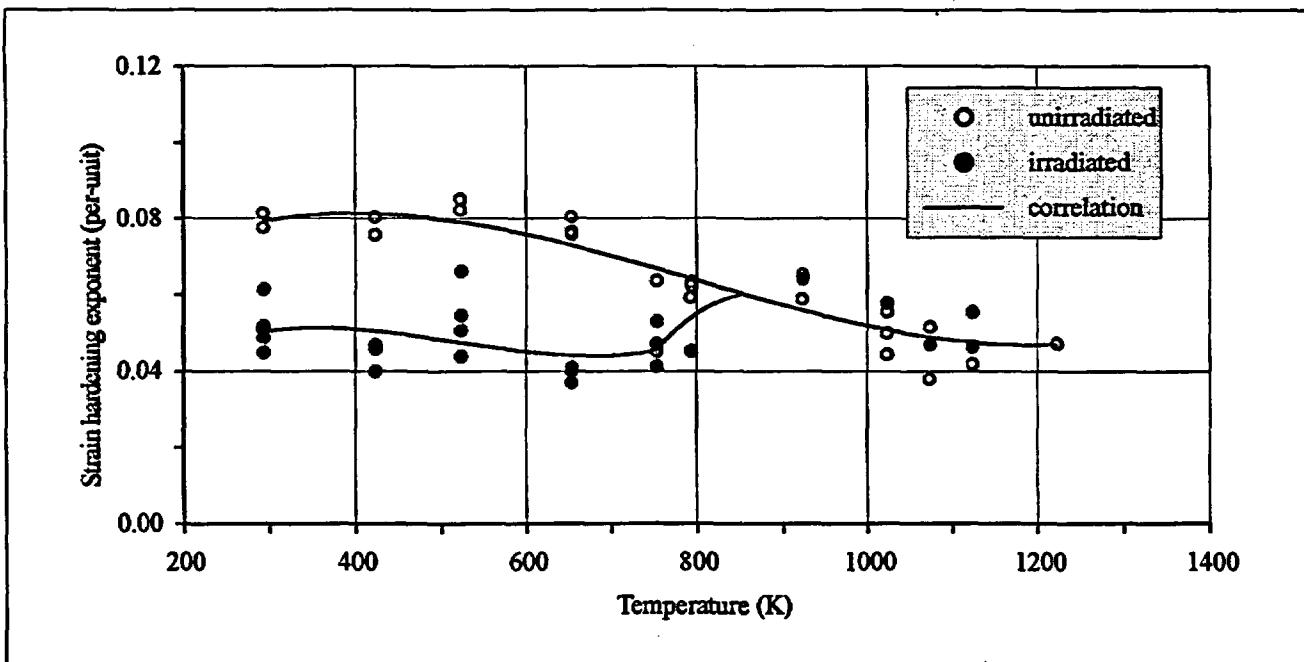


Fig. 5.11. Strain hardening exponent vs. temperature for unirradiated and irradiated Zr-1%Nb cladding.

The analysis of the data base on strain rate sensitivity exponent indicated that it was not sufficient. That's why it was proposed not to develop the correlation for the VVER cladding, but to use the original MATPRO correlation for strain rates $>0.01 \text{ l/s}$, which well enough describes the obtain data for unirradiated and irradiated Zr-1%Nb alloy (see Fig. 5.12).

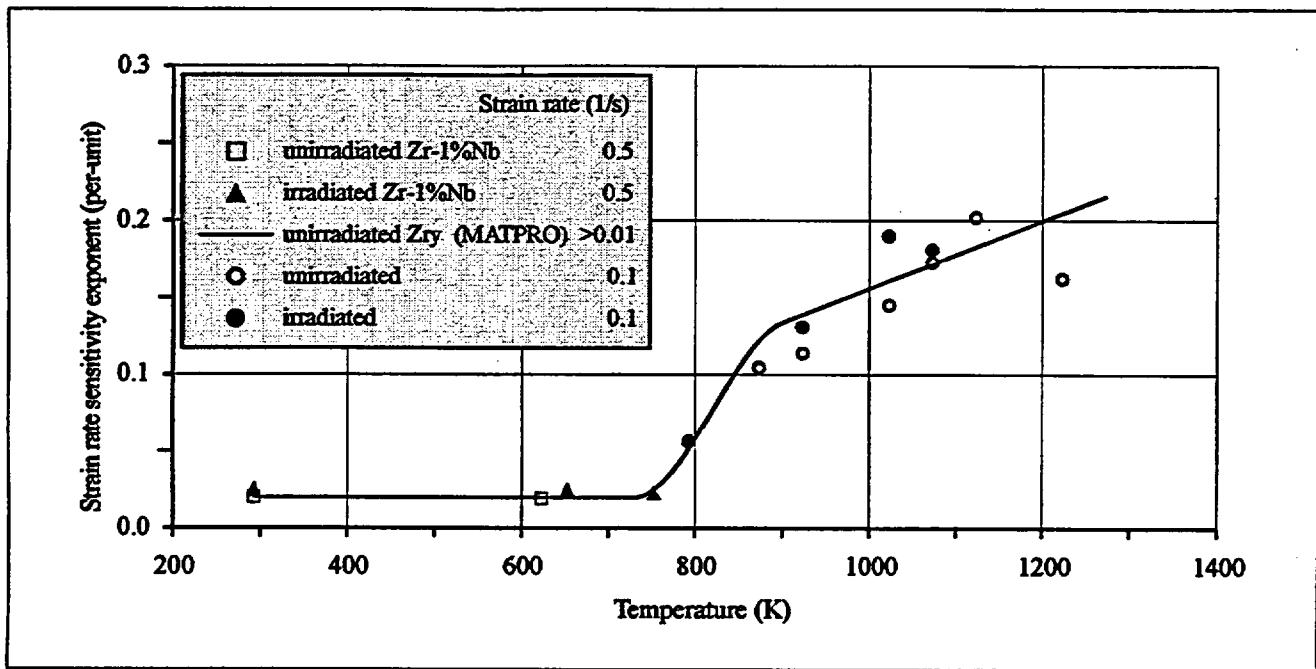


Fig. 5.12. Comparison of the strain rate sensitivity exponents for Zr-1%Nb alloy and Zircaloy.

The correlations for K, n, m parameters were incorporated into CKMN module. The listing of the module is presented in Appendix A.

5.3.4. Cladding failure criterion (CMLIMT)

The local tangential stress at burst was used as a failure criterion in the course of FRAP-T6 simulation of IGR test rods. According to the MATPRO procedure intended to derive the criterion from the Zry experimental data, the burst test data on Zr-1%Nb in the temperature range 973-1473 K served as a base to develop analogous failure criterion of VVER cladding [1]. Only the temperature dependence of burst stress was obtained because it was not revealed noticeable differences between unirradiated and irradiated cladding (see Fig. 5.13). Table 5.12 contains correlations for local burst stress which were used to predict Zr-1%Nb cladding failure.

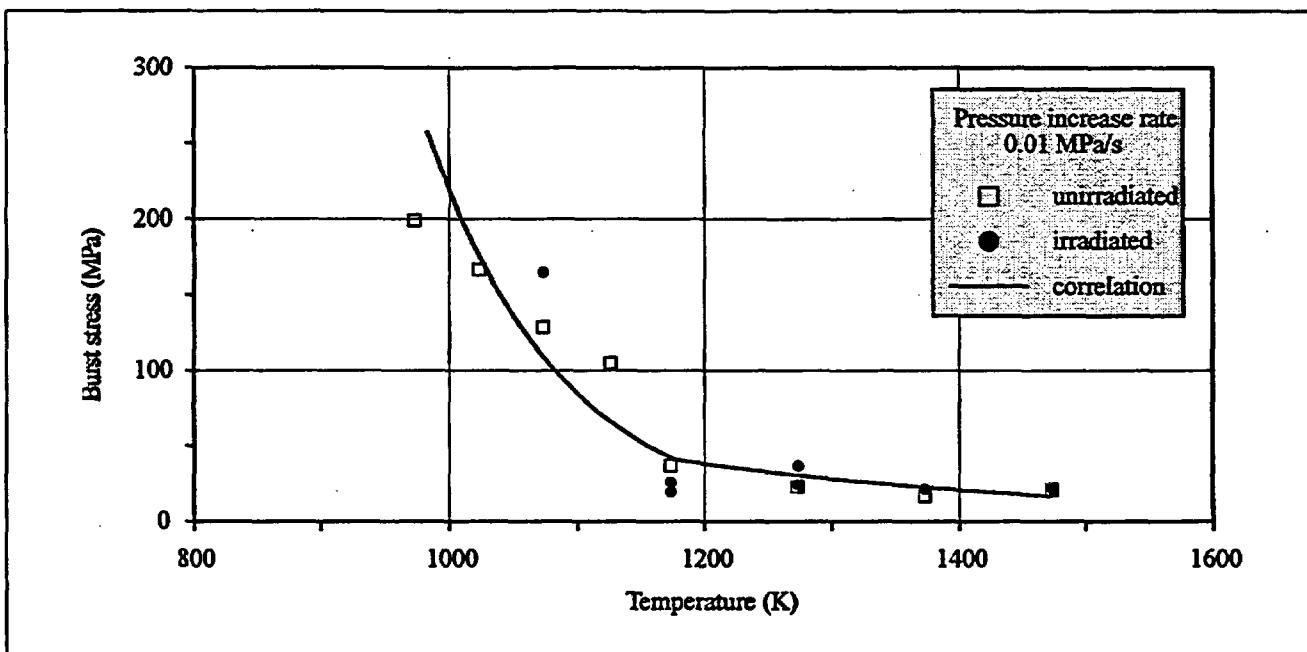


Fig. 5.13. Measured local burst stresses and new MATPRO correlation for Zr-1%Nb cladding.

Table 5.12. Correlations for local burst stress of Zr-1%Nb cladding.

Range of temperature (K)	Local burst stress (MPa) vs. temperature
$973 < T \leq 1176.44$	$\sigma_B = 2.99522 \cdot 10^6 \exp(-0.00952232 T)$
$1176.44 < T \leq 1473$	$\sigma_B = 1.41537 \cdot 10^3 \exp(-0.00301426 T)$

The listing of the module CMLIMT with incorporated Zr-1%Nb burst stress criterion is presented in Appendix A.

6. CODING ASPECTS

6.1. Description of the new global variables

The new global variables are introduced for the newly developed and modified models. Table 6.1 contains the description of the new global variables. All new global variables stored in two headers: WWER.H and WWER1.H.

The description of following common blocks is not presented here:

COMMON BLOCK /GRF_S/: This common block contains the variables for graphic package of FRAP-T6/VVER code, which allows to display thermal-mechanical parameters of fuel rod during calculation (online regime). Graphic package was developed specially for FRAP-T6 code and was used during code testing and verification. Graphic subroutines were excluded from this version of FRAP-T6 code since it demands only LAHEY translator.

COMMON BLOCK /H_COND/: This common block contains temporary parameters for printout. Parameters were applied during code testing and now are not used.

COMMON BLOCK /H/: HMIC, HMAC - variables of QDOT subroutine for post-CHF heat transfer coefficient calculated with Bromley-Pomerantz model.

Table 6.1. New global variables incorporated into FRAP-T6/VVER code.

Name	Type	Storage	Description
IWWER	INTEGER *8 constant	WWER.H COMMON /WWER/	Option for selection of VVER/PWR fuel rod design
ITEPLN	INTEGER*8 constant	WWER.H COMMON /WWER/	Option for coolant type selection
COEALF	REAL *8 constant	WWER.H COMMON /WWER/	Kutateladze subcooling factor for heat transfer coefficient in post-CHF regime
ENTH	REAL*8 array (50)	WWER.H COMMON /WWER/	Peak fuel enthalpy at each axial slice
ENTER	REAL*8 array (50)	WWER.H COMMON /WWER/	Energy deposition at each axial slice
EXIT	REAL*8 array (50)	WWER.H COMMON /WWER/	Energy leakage at each axial slice
LMAX1	INTEGER *8 constant	WWER.H COMMON /COORD/	Number of axial slice with peak power rate
ISTEPPRINT	INTEGER *8 constant	WWER.H COMMON /COORD/	Number of time steps which are exclud- ed from the output proceeding in the *.DAT files
ISWEL	INTEGER *8 constant	WWER.H COMMON /COORD/	Option for calculation of gas gap width with account for fuel swelling:
EIUNFMB	REAL *8 constant	WWER.H COMMON /LAC_BALLOON/	Uniform hoop clad strain
EISTABB	REAL *8 constant	WWER.H COMMON /LAC_BALLOON/	Instability hoop clad strain

Name	Type	Storage	Description
ERUPB	REAL *8 constant	WWER.H COMMON /LAC_BALLOON/	Clad hoop strain at clad failure
EPB	REAL *8 constant	WWER.H COMMON /LAC_BALLOON/	Plastic clad hoop strain
TIME_FAIL	REAL *8 constant	WWER.H COMMON /LAC_BALLOON/	Time at clad failure
CBRSTE	REAL *8 constant	WWER.H COMMON /LAC_BALLOON/	Clad burst stress
STRESS_BAL	REAL *8 constant	WWER.H COMMON /LAC_BALLOON/	Not used
TEMP_FAIL	REAL *8 constant	WWER.H COMMON /LAC_BALLOON/	Clad temperature at failure
PG_FAIL	REAL *8 constant	WWER.H COMMON /LAC_BALLOON/	Internal gas pressure at failure
EBURST	REAL *8 constant	WWER.H COMMON /LAC_BALLOON/	Clad hoop strain at failure
Z_BURST	REAL *8 constant	WWER.H COMMON /LAC_BALLOON/	Axial location at failure
HRADD	REAL *8 constant	WWER.H COMMON /FOR_HTRC/	Radiation component of clad-to-air heat transfer coefficient
HTC_COOL	REAL *8 constant	WWER.H COMMON /FOR_HTRC/	Gas natural convection component of clad-to-air heat transfer coefficient
HTCC	REAL *8 constant	WWER.H COMMON /FOR_HTRC/	Total clad-to-air heat transfer coefficient
KREAL	REAL *8 constant	WWER.H COMMON /FOR_HTRC/	Number of current axial slice.
TIMEHTC	REAL *8 constant	WWER.H COMMON /FOR_HTRC/	Time of clad rewetting
FMASSA	REAL *8 constant	WWER.H COMMON /GEOMETRY/	Mass of fuel in fuel rod
FDLINA	REAL *8 constant	WWER.H COMMON /GEOMETRY/	Heated length of fuel rod
FRPLOT	REAL *8 constant	WWER.H COMMON /GEOMETRY/	Fraction of fuel theoretical density
DL	REAL*8 array (50)	WWER.H COMMON /GEOMETRY/	Length of axial slice
RHOLE	REAL *8 constant	WWER.H COMMON /GEOMETRY/	Radii of central hole
SWELMAX	REAL *8 constant	WWER.H COMMON /FISGAS/	Maximum fuel swelling
FGRTOT	REAL *8 constant	WWER.H COMMON /FISGAS/	Total fission gas release
TDAY	REAL *8 constant	WWER.H COMMON /FISGAS/	Current time during base irradiation

Name	Type	Storage	Description
FGR_Z	REAL*8 array (50)	WWER.H COMMON /FISGAS/	Fission gas release at axial slice
BVS_Z	REAL*8 array (50)	WWER.H COMMON /FISGAS/	Fuel swelling at axial slice
RGJ_Z	REAL*8 array (50)	WWER.H COMMON /FISGAS/	Total gas generated in fuel that is retained in fuel matrix at axial slice
GJOUT_Z	REAL*8 array (50)	WWER.H COMMON /FISGAS/	Fraction of gas released from fuel at axial slice
RGGL_Z	REAL*8 array (50)	WWER.H COMMON /FISGAS/	Fraction of gas retained in fuel grains at axial slice
RGGF_Z	REAL*8 array (50)	WWER.H COMMON /FISGAS/	Fraction of gas retained on fuel grain faces at axial slice
RGGE_Z	REAL*8 array (50)	WWER.H COMMON /FISGAS/	Fraction of gas retained on fuel grain edges at axial slice
RGT_GR	REAL *8 constant	WWER.H COMMON /FISGAS/	Total gas generated in fuel that is retained in fuel matrix
GRFT	REAL *8 constant	WWER.H COMMON /FISGAS/	Total gas released from fuel
VOLSV	REAL *8 constant	WWER.H COMMON /FISGAS/	Fuel rod free volume
POHE	REAL *8 constant	WWER.H COMMON /FISGAS/	Internal gas pressure at the end of base irradiation
IREWET	INTEGER *8 constant	WWER.H COMMON /REWET/	Option to calculate clad rewetting time
TEMP_CONT	REAL *8 constant	WWER.H COMMON /CONTA/	Average clad temperature at the beginning of PCMI
TIME_CONT	REAL *8 constant	WWER.H COMMON /CONTA/	Time at the beginning of PCMI
EHOOP_MAX	REAL *8 constant	WWER.H COMMON /CONTA/	Maximum clad hoop strain
CONBU0	REAL *8 constant	WWER.H COMMON /CONTA/	Fuel thermal conductivity coefficient with accounting for burnup effect
CON0	REAL *8 constant	WWER.H COMMON /CONTA/	Fuel thermal conductivity coefficient without accounting for burnup effect
AX CT	REAL *8 constant	WWER.H COMMON /CONTA/	Empirical factors for fuel thermal conductivity coefficient degradation vs. burnup
DTCLADD	REAL *8 constant	WWER.H COMMON /CONTA/	Temperature drop across clad thickness
DE_DT	REAL *8 constant	WWER.H COMMON /CONTA/	Clad hoop strain rate
FBU	REAL *8 constant	WWER.H COMMON /CONTA/	Maximum fuel burnup
BURN_Z	REAL *8 array(50)	WWER.H COMMON /CONTA/	Fuel burnup at each axial slice

Name	Type	Storage	Description
JRUPTURE	INTEGER*8 constant	WWER.H COMMON /CONTA/	Clad failure indicator
GASWLP	REAL *8 constant	WWER.H COMMON /SWELL/	Gas component of fuel swelling at axial slice with peak power
SOLDSWP	REAL *8 constant	WWER.H COMMON /SWELL/	Solid component of fuel swelling at axial slice with peak power
SOLD	REAL *8 constant	WWER.H COMMON /SWELL/	Total fuel swelling at axial slice with peak power
BUARRAY	REAL *8 array(50)	WWER.H COMMON /SWELL/	Radial burnup distribution
BURNTOT	REAL *8 constant	WWER.H COMMON /SWELL/	Maximum fuel burnup
POW_RAD	REAL *8 array(50,50)	WWER.H COMMON /SWELL/	Distribution of radial power rate
COEFPOW	REAL *8 array(50,50)	WWER.H COMMON /SWELL/	Radial power rate coefficient at each axial slice
DENIRR	REAL *8 constant	WWER.H COMMON /SWELL/	Fuel density change due to irradiation-induced densification
RDEN	REAL *8 array(50)	WWER.H COMMON /SWELL/	Radial fuel displacement due to irradiation-induced densification
RSW	REAL *8 array(50)	WWER.H COMMON /SWELL/	Radial fuel displacement due to swelling
BURND	REAL *8 constant	WWER.H COMMON /SWELL/	Axially maximum fuel burnup after base irradiation
BU_EQ	REAL *8 constant	WWER.H COMMON /SWELL/	Not used
VAR_ITER	REAL *8 constant	WWER.H COMMON /CHAR/	Number of iteration at time step
SUMCR	REAL *8 array(50)	WWER.H COMMON /CRITER/	Temporary variable for clad failure criterion (strain accumulation)
DEFC	REAL *8 array(50)	WWER.H COMMON /CRITER/	Effective clad strain
EDOTW	REAL *8 constant	WWER.H COMMON /CRITER/	Effective clad strain rate
BURN_GRF	REAL *8 array(50,50)	WWER1.H COMMON /BURN/	Radial/axial burnup distribution
RBURN	REAL *8 array(50)	WWER1.H COMMON /BURN/	Radial distribution of burnup at axial slice with peak power
BU1	REAL *8 constant	WWER1.H COMMON /BURN/	Burnup at the beginning of time step at axial slice with peak power
BU2	REAL *8 constant	WWER1.H COMMON /BURN/	Burnup at the end of time step at axial slice with peak power

All the new variables are stored in two headers: WWER.H and WWER1.H.

6.2. Description of the new and modified subroutines

Table 6.2 lists the modified and new subroutines incorporated into FRAP-T6/VVER code. Table 6.2 presents description of the new and modified subroutines, including the name, status and initial function of the subroutine, as well as the main sense of the made change. The «modified» status means that the subroutine was a part of the original version of FRAP-T6 code.

Table 6.2. The list of modified and new subroutines incorporated into FRAP-T6/VVER code.

Module name	Status	Function	Nature of modification
CCP	modified	Driver for calculation of clad specific heat	Introduction of option for calculation of Zr-1%Nb clad specific heat
CCPINP	modified	Driver for calculation of clad enthalpy	Introduction of option for calculation of Zr-1%Nb clad enthalpy
CTHEXP	modified	Driver for calculation of clad thermal expansion	Introduction of option for calculation of Zr-1%Nb clad thermal expansion
CELMOD	modified	Driver for calculation of clad Young's modulus	Introduction of option for calculation of Zr-1%Nb clad Young's modulus
CTHCON	modified	Driver for calculation of clad thermal conductivity	Introduction of option for calculation of Zr-1%Nb clad thermal conductivity
CMHARD	modified	Driver for calculation of clad Mayer micro-hardness	Introduction of option for calculation of Zr-1%Nb clad Mayer hardness
EMCPIR	modified	Driver for calculation of clad Poisson's ratio	Introduction of option for calculation of Zr-1%Nb clad Poisson coefficient
CKMN	modified	Driver for calculation of K, m, n parameters of clad	Introduction of model for calculation of Zr-1%Nb clad K, m, n parameters with account for clad strain rate
CMLIMT	modified	Driver for calculation of clad short-term strength parameters	Introduction of model for calculation of Zr-1%Nb clad strength parameters with account for clad strain rate
PHYPRP	modified	Driver for calculation of fuel and thermal-physical parameters	Introduction of option for calculation of thermal-physical parameters for Zr-1%Nb clad and VVER fuel
QDOT	modified	Driver for calculation of clad-to-water coolant heat transfer	Introduction of option for calculation of clad-to-water heat transfer
HTRC	modified	Driver for calculation of clad-to-coolant heat transfer	Introduction of option for calculation of clad-to-air heat transfer
REWETT	new	Determination of clad rewetting time	Introduce into QDOT subroutine to calculate time of cladding rewetting
RIMTIM	new	Choice of radial peaking factor for power vs. time	Time dependence for power radial peaking factor
RIMMOD	new		
FINT	new		

Module name	Status	Function	Nature of modification
BURNUP	new	Determination of coefficients for calculation of fuel thermal conductivity degradation with burnup	Introduce into FTHCON subroutine to calculate fuel thermal conductivity degradation with burnup
TCOR	new	Data base for determination of VVER fuel thermal conductivity coefficients vs. temperature	Introduce into FTHCON subroutine to calculate fuel thermal conductivity coefficients vs. temperature for VVER type of fuel
FCP	modified	Driver for calculation of fuel specific heat	Introduction of option for calculation of VVER fuel specific heat
FTHEXP	modified	Driver for calculation of fuel thermal expansion	Introduction of option for calculation of VVER fuel thermal expansion
FENTHL	modified	Driver for calculation of fuel enthalpy	Introduction of option for calculation of VVER fuel enthalpy
FTHCON	modified	Driver for calculation of fuel thermal conductivity	Introduction of option for calculation of VVER fuel thermal conductivity
COBILD	modified	Driver for calculation of high temperature oxidation	Introduction of option for calculation of Zr-oxide layers for Zr-1%Nb clad
GAPTHC	modified	Calculation of clad-fuel gap thermal conductivity	Remove the bug
STORE6	modified	Driver for storing output information	Remove the bug. Establish additional parameters for printout
PCHF	modified	Driver for calculation of critical heat fluxes	Remove the bug
FRAPT6	modified	Input data processing, initialization of calculational procedures	Additional input data processing, initialization of output files GRAPH.DAT etc.
DEFORM	modified	Driver for mechanical calculation	Introduction of option for calculation of gas gap width with account for fuel swelling
GRAFOUT	modified	Driver for generation of graphic information	Generation of new graphic information. Initialization of brief listing with general output parameters
GRASF	modified	Calculation of fission gas release and fuel swelling	Generation of new output files with graphic information
GAPHTC	modified	Calculation of clad-fuel gap thermal conductivity	Remove the bug
GCONR2	modified	Calculation of clad-fuel gap thermal conductivity for the BALON2 subcode	Limitation of minimum gap width by 15 μm
FSWELL	new (from MATPRO-V11)	Driver for fuel swelling calculation under base irradiation conditions	Coupling with FRAP-T6 code

Module name	Status	Function	Nature of modification
FUDENS	new (from MATPRO-V11)	Driver for fuel densification calculation under base irradiation conditions	Coupling with FRAP-T6 code
MELT	modified	Indication of clad failure due to melting	Remove the bug
BALON2	modified	Ballooning calculation	Modification of temperature azimuthal variation
PRNTOT	modified	Output of information in output listing	Add the list of output parameters
GRAFDATA	new	Post-processing utility for STRIPF file	Generation of output information in format suitable for PC utilities.

7. USER'S MANUAL

7.1. Description of the new input data

Specification of the input data was expanded in order to account for the specific features of fuel rod testing in IGR reactor. Additional parameters occupy three first strings in the new data specification. Description of the additional input data parameters is presented in Table 7.1.

Table 7.1. List of new parameters of input data.

Parameter	Description	Type	Value
TITLE	Text string	CHARACTER*120	-
NREST	Restart	INTEGER	0
NCARDS	parameters	INTEGER	1
IUNCRT	(specified by FRAP-T6)	INTEGER	0
T1	Start calculational time (specified by FRAP-T6)	REAL*8	$-7.8 \cdot 10^7$
T2	End calculational time (specified by FRAP-T6)	REAL*8	580
ITEPLN	Coolant type (additional parameter)	INTEGER	
	<ul style="list-style-type: none"> • Water • Forced Helium • Stagnated Air • Forced Air 		0 9 10 11
IWWER	VVER/PWR type (additional parameter)	INTEGER	
	<ul style="list-style-type: none"> • Cladding – Zircalloy, Fuel - PWR type • Cladding - Zr-1%Nb, Fuel - VVER type 		0 1
IRECVR	(specified by FRAP-T6)	INTEGER	1
MPTFC2	(specified by FRAP-T6)	INTEGER	0
ISTEPPRINT	User-specified number of time steps which are excluded from the output proceeding in the *.DAT files (additional parameter)	INTEGER	20
LMAX	Number of axial fuel rod slice with peak power (additional parameter)	INTEGER	1
ISWEL	Option for calculation of gas gap width with account for fuel swelling:	INTEGER	
	<ul style="list-style-type: none"> • Swelling is not taken into account • Swelling is calculated with FS WELL subcode • Swelling is calculated with GRASF subcode 		0 1 2
TITLE	Comment	CHARACTER*10	REWET
IREWET	Option to calculate rewetting time:	INTEGER	
	<ul style="list-style-type: none"> • rewetting is not taken into account • rewetting is taken into account 		0 1

As an example, specification of the input data to analyze one of the VVER fuel rods tested in IGR reactor (#H5T) is presented below.

```
*****
* frapt6, transient fuel rod analysis code
*-----*
* CASE DESCRIPTION: IMPULSE ROD-1
*-----*
* UNIT FILE DESCRIPTION
* -----
* -- Input:
* 15 Water properties data
* -- Output:
* 6 STANDARD PRINTER OUTPUT
* 66 STRIPP FILE FOR GRAFITI
* -- Scratch:
* 5 SCRATCH INPUT FILE FROM ECHO1
* Input: FRAPT6 INPUT FILE
*-----
* NPA FLAGS
*NPAON
*NPADBG
NPAPAX='frapt6'
NPADUH='frapt6.duh'
NPASERV='unix:0.0'
*
* GOESINS:
FILE05='nullfile', STATUS='scratch', FORM='FORMATTED',
    CARRIAGE CONTROL='LIST'
FILE15='sth2xt', STATUS='old', FORM='UNFORMATTED'
*
* GOESOUTS:
FILE06='PULSE.out', STATUS='UNKNOWN', CARRIAGE CONTROL='LIST'
FILE66='stripf', STATUS='UNKNOWN', FORM='FORMATTED',
    CARRIAGE CONTROL='LIST'
*****  

    Restart Time-beg   Time-end   Coolant Clad irecvr mptfc2 => steppint, lmax
  0 1      0   -0.75e8     580.0        0  2    1  0
 10      1      0
Rew      0
#H5T Q=239 (cal/g) pre-irradiated
/iodata block
input option selecti
    si unit
end
output selection opt
    si unit option
    print interval      5.e7      5.e7
    plot output
end
end block
/power specification data block
power history input 2.1478E+00-.7805E+082.1478E+00-.7795E+082.1478E+00-.7700E+08
  2.1478E+00-.7600E+082.1541E+00-.7500E+082.1732E+00-.7400E+08
  2.1976E+00-.7300E+082.2002E+00-.7200E+082.1710E+00-.7100E+08
  2.1515E+00-.7000E+082.1687E+00-.6900E+082.1863E+00-.6800E+08
  2.1987E+00-.6700E+082.2106E+00-.6600E+082.2346E+00-.6500E+08
  2.2600E+00-.6400E+082.2735E+00-.6300E+082.2851E+00-.6200E+08
  2.2799E+00-.6100E+082.2657E+00-.6000E+082.2911E+00-.5900E+08
  2.3244E+00-.5800E+082.3398E+00-.5700E+082.3502E+00-.5600E+08
  2.3832E+00-.5500E+082.4266E+00-.5400E+082.5909E+00-.5300E+08
  2.7492E+00-.5200E+082.8379E+00-.5100E+082.8255E+00-.5000E+08
  2.8165E+00-.4900E+082.8165E+00-.4800E+082.8001E+00-.4700E+08
  2.7118E+00-.4600E+082.6706E+00-.4500E+082.6635E+00-.4400E+08
  2.6365E+00-.4300E+082.6081E+00-.4200E+082.5942E+00-.4100E+08
  2.5733E+00-.4000E+082.5377E+00-.3900E+082.5340E+00-.3800E+08
  2.5598E+00-.3700E+082.5845E+00-.3600E+082.5729E+00-.3500E+08
```

2.5613E+00 - .3400E+082.5542E+00 -.3300E+082.5478E+00 -.3200E+08
 2.5463E+00 -.3100E+082.5463E+00 -.3000E+082.5314E+00 -.2900E+08
 2.5516E+00 -.2800E+082.4992E+00 -.2700E+082.4468E+00 -.2600E+08
 2.4329E+00 -.2500E+082.2597E+00 -.2400E+082.1942E+00 -.2300E+08
 2.1583E+00 -.2200E+082.1938E+00 -.2100E+082.2297E+00 -.2000E+08
 2.2020E+00 -.1900E+082.1556E+00 -.1800E+082.1803E+00 -.1700E+08
 2.2121E+00 -.1600E+082.2121E+00 -.1500E+082.2121E+00 -.1400E+08
 2.2121E+00 -.1300E+082.2144E+00 -.1200E+082.2305E+00 -.1100E+08
 2.2223E+00 -.1000E+082.1938E+00 -.9000E+072.1863E+00 -.8000E+07
 2.1863E+00 -.7000E+072.1968E+00 -.6000E+072.2110E+00 -.5000E+07
 2.2121E+00 -.4000E+072.2043E+00 -.3000E+072.1916E+00 -.2000E+07
 2.1863E+00 -.1000E+072.5090E+00 -.1000E+06 .0000 -.2000E+04
 0.0000E+000.0000E+000.3300E-010.5000E-010.6700E-010.1000E+00
 0.1000E+000.1500E+000.1340E+000.2000E+000.1670E+000.2500E+00
 0.2000E+000.3000E+000.2340E+000.3500E+000.2670E+000.4000E+00
 0.3000E+000.4500E+000.3340E+000.5000E+000.3670E+000.5500E+00
 0.4010E+000.6000E+000.4340E+000.6500E+000.4680E+000.7000E+00
 0.5010E+000.7500E+000.5350E+000.8000E+000.5680E+000.8500E+00
 0.6320E+000.9000E+000.7010E+000.9500E+000.7780E+000.1000E+01
 0.8610E+000.1050E+010.9520E+000.1100E+010.1050E+010.1150E+01
 0.1160E+010.1200E+010.1270E+010.1250E+010.1400E+010.1300E+01
 0.1540E+010.1350E+010.1680E+010.1400E+010.1850E+010.1450E+01
 0.2020E+010.1500E+010.2210E+010.1550E+010.2410E+010.1600E+01
 0.2640E+010.1650E+010.2880E+010.1700E+010.3140E+010.1750E+01
 0.3420E+010.1800E+010.3730E+010.1850E+010.4070E+010.1900E+01
 0.4430E+010.1950E+010.4830E+010.2000E+010.5260E+010.2050E+01
 0.5730E+010.2100E+010.6250E+010.2150E+010.6810E+010.2200E+01
 0.7430E+010.2250E+010.8100E+010.2300E+010.8840E+010.2350E+01
 0.9660E+010.2400E+010.1060E+020.2450E+010.1150E+020.2500E+01
 0.1260E+020.2550E+010.1390E+020.2600E+010.1520E+020.2650E+01
 0.1670E+020.2700E+010.1840E+020.2750E+010.2020E+020.2800E+01
 0.2230E+020.2850E+010.2450E+020.2900E+010.2700E+020.2950E+01
 0.2980E+020.3000E+010.3280E+020.3050E+010.3600E+020.3100E+01
 0.3940E+020.3150E+010.4270E+020.3200E+010.4570E+020.3250E+01
 0.4810E+020.3300E+010.4900E+020.3350E+010.4760E+020.3400E+01
 0.4420E+020.3450E+010.3980E+020.3500E+010.3520E+020.3550E+01
 0.3080E+020.3600E+010.2670E+020.3650E+010.2310E+020.3700E+01
 0.2000E+020.3750E+010.1730E+020.3800E+010.1510E+020.3850E+01
 0.1310E+020.3900E+010.1150E+020.3950E+010.1010E+020.4000E+01
 0.8890E+010.4050E+010.7860E+010.4100E+010.7000E+010.4150E+01
 0.6250E+010.4200E+010.5610E+010.4250E+010.5050E+010.4300E+01
 0.4570E+010.4350E+010.4150E+010.4400E+010.3780E+010.4450E+01
 0.3450E+010.4500E+010.3170E+010.4550E+010.2920E+010.4600E+01
 0.2690E+010.4650E+010.2500E+010.4700E+010.2320E+010.4750E+01
 0.2160E+010.4800E+010.2010E+010.4850E+010.1890E+010.4900E+01
 0.1770E+010.4950E+010.1660E+010.5000E+010.1570E+010.5050E+01
 0.1480E+010.5100E+010.1400E+010.5150E+010.1290E+010.5200E+01
 0.1230E+010.5250E+010.1180E+010.5300E+010.1130E+010.5350E+01
 0.1090E+010.5400E+010.1050E+010.5450E+010.1010E+010.5500E+01
 0.9660E+000.5550E+010.9300E+000.5600E+010.8950E+000.5650E+01
 0.8620E+000.5700E+010.8310E+000.5750E+010.8020E+000.5800E+01
 0.7740E+000.5850E+010.7470E+000.5900E+010.7220E+000.5950E+01
 0.6990E+000.6000E+010.6760E+000.6050E+010.6540E+000.6100E+01
 0.6340E+000.6150E+010.6150E+000.6200E+010.5960E+000.6250E+01
 0.5790E+000.6300E+010.5630E+000.6350E+010.5470E+000.6400E+01
 0.5320E+000.6450E+010.5170E+000.6500E+010.5040E+000.6550E+01
 0.4910E+000.6600E+010.4780E+000.6650E+010.4660E+000.6700E+01
 0.4550E+000.6750E+010.4440E+000.6800E+010.4340E+000.6850E+01
 0.4240E+000.6900E+010.4150E+000.6950E+010.4060E+000.7000E+01
 0.3970E+000.7050E+010.3890E+000.7100E+010.3810E+000.7150E+01
 0.3730E+000.7200E+010.3660E+000.7250E+010.3590E+000.7300E+01
 0.3530E+000.7350E+010.3460E+000.7400E+010.3400E+000.7450E+01
 0.3340E+000.7500E+010.3280E+000.7550E+010.3230E+000.7600E+01
 0.3170E+000.7650E+010.3120E+000.7700E+010.3070E+000.7750E+01
 0.3030E+000.7800E+010.2980E+000.7850E+010.2940E+000.7900E+01
 0.2890E+000.7950E+010.2850E+000.8000E+010.2460E+000.9000E+01
 0.1980E+000.1000E+020.1550E+000.1100E+020.1330E+000.1200E+02
 0.1150E+000.1300E+020.1000E+000.1400E+020.8800E-010.1500E+02
 0.7800E-010.1600E+020.6900E-010.1700E+020.6300E-010.1800E+02
 0.5700E-010.1900E+020.5200E-010.2000E+020.4700E-010.2100E+02
 0.4400E-010.2200E+020.4100E-010.2300E+020.3800E-010.2400E+02
 0.3600E-010.2500E+020.3400E-010.2600E+020.3200E-010.2700E+02
 0.3000E-010.2800E+020.2900E-010.2900E+020.2700E-010.3000E+02
 0.1600E-010.4500E+020.1000E-010.6000E+020.7000E-020.7500E+02

```

0.5000E-020.9000E+020.3000E-020.1050E+030.3000E-020.1200E+03
0.2000E-020.1350E+030.2000E-020.1500E+030.1000E-020.1650E+03
0.1000E-020.1800E+030.1000E-020.2300E+030.1000E-020.2800E+03
0.0000E+000.4800E+030.0000E+000.5300E+030.0000E+000.5800E+03
axial power profile .1128E+01 .0000E+00 .1128E+01 .4500E-02 .1128E+01 .9500E-02
                .1128E+01 .1450E-01 .9926E+00 .1950E-01 .9926E+00 .2450E-01
                .9926E+00 .2950E-01 .9813E+00 .3450E-01 .9813E+00 .3950E-01
                .9813E+00 .5950E-01 .1004E+01 .6450E-01 .9926E+00 .6950E-01
                .9813E+00 .7450E-01 .9700E+00 .7950E-01 .9588E+00 .8450E-01
                .9588E+00 .8950E-01 .9588E+00 .9450E-01 .9700E+00 .9950E-01
                .9813E+00 .1045E+00 .9813E+00 .1095E+00 .9588E+00 .1145E+00
                .9700E+00 .1195E+00 .9813E+00 .1245E+00 .9926E+00 .1295E+00
                .9926E+00 .1560E+00
radial power profile1.0000E-9 0.0 1.0000E-9 0.0010E-02 1.000E-9 0.1200E-02
                0.9297E+000.1201E-020.9297E+000.1659E-020.9297E+000.1845E-02
                0.9297E+000.2014E-020.9328E+000.2170E-020.9390E+000.2316E-02
                0.9452E+000.2452E-020.9514E+000.2582E-020.9575E+000.2705E-02
                0.9637E+000.2824E-020.9699E+000.2937E-020.9761E+000.3046E-02
                0.9911E+000.3151E-020.1015E+010.3253E-020.1039E+010.3352E-02
                0.1062E+010.3448E-020.1086E+010.3541E-020.1188E+010.3632E-02
                0.1369E+010.3721E-020.1868E+010.3790E-02
multiplier 8.20
end block
/design of fuel rod data block
fuel rod data      0.156  9.100e-03   293.4
pellet data        .000e-3  0.000e-3  11.00e-3  0.000e-6  7.58e-3  2.00
                .96800          0.e3    0.000       2.0      1883.      6.
cladding data     0.060e-3      0.0      2.0           0.0      0.0
upper plenum data 1      .100e-3   5.00e-3   1.00e-3   4.440e-6
lower plenum data 1      .100e-3   5.00e-3   1.00e-3   0.357e-6
gas composition   0.9757  0.0243      0.0      0.0      1.65e+6   293.4
end block
/solution control data block
property initializat
                fuel conductivity      50      273.      5000.
                cladding conductivit  50      273.      4000.
end
time control
                time step specifica 1.00e5      -10.e+7  1.00e5      -7.7e7
                1.00e5            -7.7e+7  1.00e5      -1.e5
                1.00e4            -5.0e+4  1.00e4      -1.e4
                0.010             0.0      0.010      0.02
                0.005             0.02     0.005      5.
                0.010             5.0      0.010      12.
                0.05              12.      0.05      30.
                10.0              30.      10.0      1000.
                steady-state        500.
end
convergence control
                implicit calculation .001      .001
                temperature computat 300      300      1.0
end
nodalization
                axial nodalization    10
                fuel radial nodaliza  25
                cladding radial noda  6
end
end block
/model selection data block
heat conduction
                central void        0.0      0.156      1.20e-3
deformation model
internal gas press
                plenum
                grass
metal-water
                cathcart
end block
/boundary condition data block
coolant conditions
                geometry           1.e0      1.e0      0.75
                lower pl enthalpy  1360.0e3  -10.e7    1360.e3  -5.e4
                85.0e3            0.0      100.e3    620.

```

```

pressure          15.7e6   -10.e7    15.7e6   -5.e4
                  0.1e6     0.0      0.1e6    620.
mass flux         1.e+6    -10.e7    1.e+6   -5.e4
                  1.e-6     0.0      1.00e-6  620.
core average enth. 1360.0e3  -10.e7   1360.e3  -5.e4
                  85.0e3    0.0      100.e3   620.
chf correlation  w-3
film boiling      dougall

end block
/tunning
crit             0.93
end block
/end

```

7.2. Description of the output information

7.2.1. Output file FGR_AXIS.DAT

To output the information on the dynamics of fission gas release the following additional output files are necessary in GRASF subroutine. File FGR_AXIS.DAT is formed in GRASF subroutine. The following data for the maximum power axial slice of the fuel rod under the base irradiation conditions are stored in that file. Table 7.2 presents the description of parameters.

Table 7.2. Description of parameters in FGR_AXIS.DAT file.

Variable	Description	Units
TDAY	Time	days
J	Number of axial slice	-
BVSJ(J)	Volume swelling of fuel at axial slice	%
RGJ	Gas retention in fuel matrix at axial slice	moles
GJOUT	Total gas released from fuel at axial slice	moles
RGGL	Fraction of gas retention in fuel grains at axial slice	moles
RGGF	Fraction gas retention on grain faces at axial slice	moles
RGGE	Fraction gas retention on grain edges at axial slice	moles
FGRJ/AVN	Fission gas release at axial slice at axial slice	per-unit
SUMRET	Fractional sum of retained gas in fuel at axial slice	per-unit
TK(1,J)/1.D0	Fuel temperature in inner ring at axial slice	K
TS(1,J)	Fuel temperature at outer surface of first ring at axial slice	K
TS(KF,J)	Fuel temperature at outer fuel surface at axial slice	K
POW(J)/0.3048D0	Power rate at axial slice	kW/m
BURN(J)	Fuel burnup at axial slice	MWd/kg

7.2.2. Output file FGR_TRAN.DAT and FGR_TOT.DAT

File FGR_TRAN.DAT is also formed in GRASF subroutine. The overall data for fuel rod during the non-steady-state process are stored in that file. Table 7.3 presents the description of parameters.

Table 7.3. Description of parameters in FGR_TRAN.DAT file.

Variable	Description	Units
TS0_S	Time	s
FGRT	Total gas released from fuel at axial slice	per-unit
RGT*22400.D0	Gas retention in fuel matrix at axial slice	cm ³
GTOUT*22400.D0	Gas release from fuel matrix at time step at axial slice	cm ³
GRFT*22400.D0	Gas release from fuel matrix step at axial slice	cm ³
GGT*22400.D0	Gas generation	cm ³
ERR*100.D0	Relative error in integration	%
RETI*22400.D0	Total iodine retained in fuel rod	cm ³
RETC*22400.D0	Total cesium retained in fuel rod	cm ³
OUTI*22400.D0	Total iodine released in fuel rod	cm ³
OUTC*22400.D0	Total cesium released in fuel rod	cm ³
TS(1,LMAX1)/1.0D0	Fuel temperature at inner fuel surface at axial slice with peak power	K
TS(KF,LMAX1)/1.0D0	Fuel temperature at outer fuel surface at axial slice with peak power	K

FGR_TOT.DAT file contains the same output data block for steady-state calculation of fission gas release, but time variable named as TS0PD/(3600.D0*24.D0) [days] is used instead of TS0_S [s].

7.2.3. Output files FGR_RADS.DAT and FGR_RADT.DAT

Files FGR_RADS.DAT and FGR_RADT.DAT are necessary to output the calculated data characterizing fission gas radial distribution. The files are initialized in the GRASF subroutine. The only difference in calculated data of these files is that FGR_RADS.DAT file stores the information by the end of the base irradiation conditions (pre-transient conditions), and FGR_RADT.DAT file stores the information after the pulse testing. Below we present the list of parameters for one of the output files. The calculated data are stored for the maximum power slice which is defined by the LMAX1 variable (see Table 7.4).

Table 7.4. Description of parameters in FGR_RADS.DAT and FGR_RADT.DAT files.

Variable	Description	Units
K	Number of fuel ring	-
OTN_RAD	Relative fuel radius	per-unit
RGKJ(K,J)*UNLESS	Fraction of gas retention	per-unit
TS(K,J)	Fuel temperature at inner surface of fuel pellet	K
BVSKJ(K,J)	Volume swelling of fuel	%
GOU(K,J)*UNLESS/AVN	Fractional gas release	per-unit
G_FACE (K,J)*UNLESS	Fraction of gas retention on grain faces	per-unit
G_EDGE (K,J)*UNLESS	Fraction of gas retention on grain edges	per-unit
G_GRAIN(K,J)*UNLESS	Fraction of gas retention in fuel grains	per-unit
((GSG(K,J)/AVN)/ARA(K,J))/GPE LL	Sum of gas retention	per-unit
RS(K,J)*10.D0	Fuel ring radius	cm
(G_FACE(K,J)+G_EDGE(K,J)+G_ GRAIN(K,J))*22.4D3/ RMASS	Specific gas retention	cm ³ /g fuel
PRF_GRF(K,J)	Fuel porosity	per-unit

7.2.4. Output files BALOON1.DAT, BALOON2.DAT

These output files contain time dependent thermal and mechanical parameters specially for ballooning effect. Thermal and mechanical parameters are given at user specified clad node (K,J), where K-axial coordinate, J-azimuthal coordinate.

In the case of ballooning absence empty files are formed. Table 7.5 and Table 7.6 present the list of parameters.

Table 7.5. Description of parameters in BALOON1.DAT file.

Variable	Description	Units
TIMBAL	Time	s
CTEMP(K,J)	Clad temperature	K
STRESF(K,J)*1.E-6	Effective clad stress	MPa
CTSTRT*1.E-6	Clad ultimate strength	MPa
RSTRAN(K,J)	Clad strain rate	1/s
FTEMP(K,J)	Fuel surface temperature	K
STEMP(K,J)	Not used	-
HTCS(K,J)	Not used	-
TSTM(K,J)	Not used	-
STRNC(K,J)*1.D2	Tangential component of true plastic strain	%
STRNA(K,J)*1.D2	Axial component of true plastic strain	%
STRNA(K,J+8)*1.D2	Axial component of true plastic strain	%

Table 7.6. Description of parameters in BALOON2.DAT file.

Variable	Description	Units
TIMBAL	Time	s
GPTHLU(K,J)*1.D3	Gap width	m
CTEMP(K,J)	Clad temperature	K
PSBAL/1.D6	Gas pressure	MPa
TCE*100.D0	Clad ballooning strain	%
BRATE	Clad strain rate in ballooning	K/s
STRNC(K,J)	Tangential component of true plastic strain	per-unit
RCLA	Not used	-
RAVE(K)	Azimuthally averaged midwall clad radius at axial node	m
RBAR	Not used	-
EIUNFMB	Not used	-
EISTABB	Clad instability strain	per-unit
RAD(K,J)	Current midwall clad radius	m
DISP(K,J)	Not used	-
HTCGLU(J,K)	Gap conductance in ballooning region	kW/m ² K
QLBAL(K,J)	Not used	-
QBAL	Not used	-

7.2.5. Output file GRAPH.DAT

Additional calculated data and their output format are formed in the GRAFOUT subroutine. Integral thermal-physical and thermal-mechanical parameters versus time are stored in the GRAPH.DAT file. Table 7.7 presents the list of parameters.

Table 7.7. Description of parameters in GRAPH.DAT file.

Variable	Description	Units
T_S	Time	s
ENS_MAX	Not used	-
POW	Average power of fuel rod	kW
ENTER(LMAX1)	Peak energy deposition	cal/g fuel
TGAS	Gas plenum temperature	K
ENTH(LMAX1)	Peak fuel enthalpy	cal/g fuel
TAVE	Average fuel temperature	K

Variable	Description	Units
T_S	Time	s
EXIT(LMAX1)	Peak energy leakage	cal/g fuel
SUM*100.D0	Fraction of molten zone	%
PGAS	Internal gas pressure	MPa
E1	Ave. energy deposition	cal/g fuel
E2	Energy leakage	cal/g fuel
E3	Average fuel enthalpy	cal/g fuel
CLADAXEX	Total clad axial elongation	mm
FSAXEX	Total Fuel axial elongation	mm
HT_MODEL	Heat transfer indicator	per-unit
RT2*2.0D3	Outer diameter of fuel pellet	mm
RO1*2.0D3	Inner diameter of clad	mm
RO2*2.0D3	Outer diameter of fuel rod	mm
TOTMWR	Energy of metal-water reaction	cal/g fuel
FFR(1)	Failure probability	per-unit
RT1*2.0D3	Central hole diameter	mm
SWELMAX*100.D0*3-SWEL_0	Transient volume fuel swelling	%
FGRTOT*100.D0-FGR_0	Transient total FGR	%
H_GAP	Gap thermal conductance	W/m ² K
H_GAS	Gas conductance	W/m ² K
H_SOLID	Gap conductance due to PCMI	W/m ² K
H_RAD	Gap conductance due to radiation	W/m ² K
H_FUEL	Thermal conductance from fuel to spring	W/m ² K
H_ECSP+H_ECCL	Not used	-
H_IZL	Thermal conductance from spring due to radiation	W/m ² K
H_COND	Spring-clad thermal conductance	W/m ² K
TSPRING	Spring temperature	K
TCLADDI	Clad temperature in plenum region	K
TFBOT	End of fuel stack temperature	K
HTCC	Not used	-
HTC_COOL	Not used	-
HRADD	Not used	-

Variable	Description	Units
T_S	Time	s
FLUX_PL	Heat flux from spring to clad	W/m ² K
(TPLENB+459.69D0)/1.8D0	Lower plenum temperature	K
BIO	Not used	-
FO	Not used	-
TETA1	Not used	-
TETA2	Not used	-
TAUCON	Not used	-
TAUF	Not used	-
TETA_AVER	Not used	-
TCONSTANT	Not used	-
DENIRR	Not used	-
RSW(LMAX1)*FT*1.D3	Fuel radial displacement due to swelling	mm
RDEN(LMAX1)*FT*1.D3	Fuel radial displacement due to densification	mm
SWTOT	Total fuel radial displacement	mm
HFL_GRF(LMAX1)*FLUX/THOU	Heat flux from fuel rod at axial slice with peak power rate	kW/m ²
TCLADD	Outer clad Temperature	K

7.2.6. File BRIEF.OUT (brief listing)

BRIEF.OUT file stores the limiting thermal-physical and thermal-mechanical fuel rod parameters in the form of listing, as well as the selected options of the main calculational models. Storing of data into the BRIEF.OUT file is formed in the GRAFOUT subroutine. Table 7.8 presents the description of parameters.

Table 7.8. Description of parameters in BRIEF.OUT file.

Variable	Description	Units
ENTER(LMAX1)	Maximum energy deposition	cal/g
SEFF_MAX	Maximum effective stress	MPa
E1	Average energy deposition	cal/g
SIGH_MAX	Maximum hoop stress	MPa
FKE	Maximum to average deposition ratio	-
SIGZ_MAX	Maximum axial stress	MPa
ENTH_MAX	Maximum fuel enthalpy	cal/g
EHOOP_MAX	Maximum hoop strain	%
ENS_MAX	Average fuel enthalpy	cal/g

Variable	Description	Units
100.D0*TCEBAL	Ballooning strain	%
FK_ENTH	Enthalpy to energy ratio	-
TFU_COM	Maximum fuel temperature	K
TIME_FU	Time at peak fuel temperature	s
TCL_COM	Maximum clad temperature	K
TIME_CL	Time at peak clad temperature	s
IFAIL	Failure indicator	-
MODFD	Deformation model indicator	-
TIME_FAIL	Failure time	s
ENER_FAIL	Maximum fuel energy at failure	cal/g
ENTH_FAIL	Maximum fuel enthalpy at failure	cal/g
FGR_0	Pre-transient FGR	%
TEMP_FAIL	Outer clad temperature at failure	K
FGR_END	Transient FGR	%
TSR_FAIL	Average clad temperature at failure	K
TIN_FAIL	Inner clad temperature at failure	K
TFAV_FAIL	Average fuel temperature at failure	K
BURND	Maximum burnup	MWd/kg U
PG_FAIL	Gas pressure at failure	MPa
STRES_FAIL	Hoop stress at failure	MPa
TEMP_CONT	Average clad temp at PCMI	K
TIME_CONT	Beginning of PCMI time	s
DTCLM	Peak clad temperature rate	K/s
DECLM	Peak hoop strain rate	%/s
MOLT_MAX*100.D0	Peak fraction of fuel molten zone	%
RTM	Peak radius of fuel molten zone	mm
TOTMWR	Total energy of Zr-water reaction	cal/g
ZRO2_MAX	ZrO ₂ layer	μm
ZRO_MAX	Oxygen stabilized thickness	μm
ZRO2_MAX+ZRO_MAX	Sum of oxide layers	μm
(ZRO2_MAX+ZRO_MAX)*0.75	Fraction of oxidized clad thickness	%
Z_BURST*1000.D0	Axial crack location	mm

7.2.7. Post-processing utility for the STRIPF file

Special GRAFDATA code to process the standard output STRIPF file has been developed.

The following parameters serve as the input data to process the STRIPF file (see Table 7.9).

Table 7.9. Description of input parameters for post-processing utility.

Variable	Description	Units
TEND	final transient time	s
DZ0	initial elevation of the fuel rod active part	m
LMAX	number of maximum power slice	-
NAXN	number of axial slices	-
ISTEPPRINT	number of time steps which are excluded from the output proceeding in the files.	-

These parameters are specified in the first string of the T file in succession in the free format. The processed parameters can be specified by the user directly in the T file, or they can be automatically stored when FRAP-T6/VVER code is in operation.

The following files are generated as the result of processing of the main output STRIPF file (see Table 7.10).

Table 7.10. Description of output parameters for post-processing utility.

File name	Variable description	Units
CLADAXSS.DAT	Clad axial stress	MPa
CLADHSN.DAT	Cladding hoop strain	%
CLADHSS.DAT	Cladding hoop stress	MPa
CLADITE.DAT	Cladding inner temperature	K
CLADOTE.DAT	Cladding outer temperature	K
CLADPASN.DAT	Clad permanent axial strain	%
CLADPHSN.DAT	Clad permanent hoop strain	%
CLADPRSN.DAT	Clad permanent radial strain	%
CLADRSN.DAT	Cladding radial strain	%
CLADSNLDAT	Clad instability strain	%
CLADSSLIDAT	Clad stress at instability	MPa
CLADYSS.DAT	Clad yield stress	MPa
COLBLKTE.DAT	Coolant bulk temperature	K
COLMSFLX.DAT	Coolant mass flux	kg/m ² s
COLPE.DAT	Coolant pressure	MPa
COLQL.DAT	Coolant quality	per-unit
CRTHTFLX.DAT	Critical heat flux	MW/m ²
CTEMP.DAT	Centerline temperature	K
EFCLADSS.DAT	Effective clad stress	MPa
ELEV.DAT	Nodal elevation	m

File name	Variable description	Units
FSDSP.DAT	Fuel surface displacement	mm
FSTEMP.DAT	Fuel surface temperature	K
GAPHTC.DAT	Gas gap heat conductance coefficient	kW/m ² K
GAPPR.DAT	Gap pressure	MPa
HEATTRMD.DAT	Heat transfer mode	per-unit
IOXTN.DAT	Inner oxide thickness	μm
LOCRODPW.DAT	Local fuel rod power	kW/m
METWRE.DAT	Metal-water reaction	cal/g
OOXTN.DAT	Outer oxide thickness	μm
OXSTN.DAT	Oxygen stabilized thickness	μm
STRUCIP.DAT	Structural gap interfacial pressure	MPa
STRUCRG.DAT	Structural radial gap	μm
SURHTC.DAT	Surface heat transfer coefficient	kW/m ² K
SURHTFLX.DAT	Surface heat flux	kW/m ²
THMGAPIP.DAT	Thermal gap interfacial pressure	MPa
THMRG.DAT	Thermal radial gap	μm
INDATA.DAT	Integral fuel rod data	-

7.3. Comments on the users and developers of FRAP-T6/VVER code

Description of the modified FRAP-T6 code presented above should be viewed only as adaptation of the models for computer analysis of the fuel rod behavior under the pulse testing conditions in IGR reactor. The code accounts for the major specifics of the IGR tests and the design of experimental fuel rods. Choice of the nodalization diagram and specification of the input data with consideration of the design specifics of experimental fuel rods and the capsule were performed to model the fuel rod geometry and the conditions for heat transfer in the capsule.

7.3.1. The limits for applicability of the adapted FRAP-T6/VVER code

1. The adapted FRAP-T6/VVER code is intended to model the behavior of experimental fuel rods under the IGR conditions. Verification of the separate models and the whole FRAP-T6/VVER version was mainly performed for the specific conditions of IGR reactor. Hence, the authors do not recommend to use this version of the code to model the fuel rod behavior in the conditions sufficiently different from those discussed in this report.
2. Analysis of the regimes with the complete or partial melting of the fuel is beyond the capabilities of the code. Fragmentation of the fuel and cladding are not modeled. Beginning of the fuel melting corresponds to the fuel peak enthalpy higher than ~220 cal/g (radially averaged). Hence, for interpretation of the calculated results higher than this value, it is necessary to remember that in the code there are no models analyzing fuel melting.
3. Physical and mechanical properties of the cladding of Zr-1%Nb alloy were mainly obtained for the temperature range up to 1573 K. Extrapolation of the data is used in case there are no experimental data

for higher temperatures. From this stand point modeling of the cladding behavior at the temperatures exceeding this limit can not be considered correct.

4. The models analyzing behavior of fuel, fission gas in the rim-layer, and fuel cracking are desirable to be improved further correction and improvement. For example, the model of gas release does not account for recrystallization of the fuel grain in the fuel external layer. This can result in the underestimation of the fission gas release under the pulse heating up. Recrystallized fuel layer produces a stronger mechanical interaction with the cladding because of the increased gas pressure in the pores if the temperature loadings are present. Still the verification procedures performed for the main integral parameters (fission gas release, cladding temperature, internal gas pressure in fuel rod, cladding deformation) allow to make a conclusion on the applicability of the code till the burnup of 50 MWd/kg U.

7.3.2. Further development of the adapted version of FRAP-T6 code

1. Computer analysis of the fuel rod behavior under high rates of heating (more than 1000 K/s) and deformations (100 %/s) indicated that the code iteration methods of obtaining solutions to the system of equations converge only weakly. Hence, instability of solutions (in particular, thermal conductivity in the gas gap) often takes place in the area of strongly non-linear equations of the material state. In the future it will be desirable to use more powerful numerical convergence methods for the better accuracy of calculations when modeling fast accident processes.
2. Improvements can be made in the models analyzing behavior of high burnup fuel. Special attention should be paid to modeling of the rim-zone with consideration of the fuel properties degradation, and potential cracking in case of pellet cladding mechanical interaction (PCMI).
3. Development and selection of criteria for the cladding failure under RIA conditions is currently one of the most important problems in evaluating fuel rod reliability.
4. Assumption of the thin-wall cladding is one of the main approximations in the model of the cladding mechanical behavior. Still, in case of the fast pulse heating of the cladding, temperature drop across the wall width can be of several hundreds of degrees. For these conditions, the analysis should account for the radial and thermal components of the cladding stresses.
5. Lack of the model for the stress-strain condition of the fuel can lead to the inadequate prediction of the cladding behavior in case of PCMI under the conditions of the fuel cracking (especially in case of adiabatic power peaks). To obtain spatial distribution of the stresses and deformations in the fuel it is expedient to review equations of thermal elasticity supplemented with the plastic deformation components.
6. Analysis has shown that there is a problem in prediction of the ZrO₂ thickness for the IGR tests. Measured results have demonstrated that the ZrO₂ thickness are in the range of 0-12 μm (excluding #H3T fuel rod with fuel and cladding melting). However, original models for the cladding oxidation for zircalloy and Zr-1%Nb predict the oxide thickness below 2 μm. Thus, this problem should be carefully studied in future.

8. CALCULATION EXAMPLES

8.1. The example of calculated results of the VVER fuel rod behavior under testing conditions in IGR reactor

Analysis of the experimental fuel rod (#H5T) behavior in IGR reactor is presented as the Example Problem. The fuel in #H5T fuel rod has reached the burnup of 49 MWd/kg U. Specification of the input data is presented in section 7.1 of the User's Manual chapter.

Analysis of the fuel rod main thermal-mechanical parameters consists of two stages:

1. Base irradiation conditions in the power reactor.
2. Pulse heat-up under IGR test conditions.

The recommended nodalization diagram of the fuel rod and main parameters of the input data specification are presented in Fig. 8.1 and in Table 8.1.

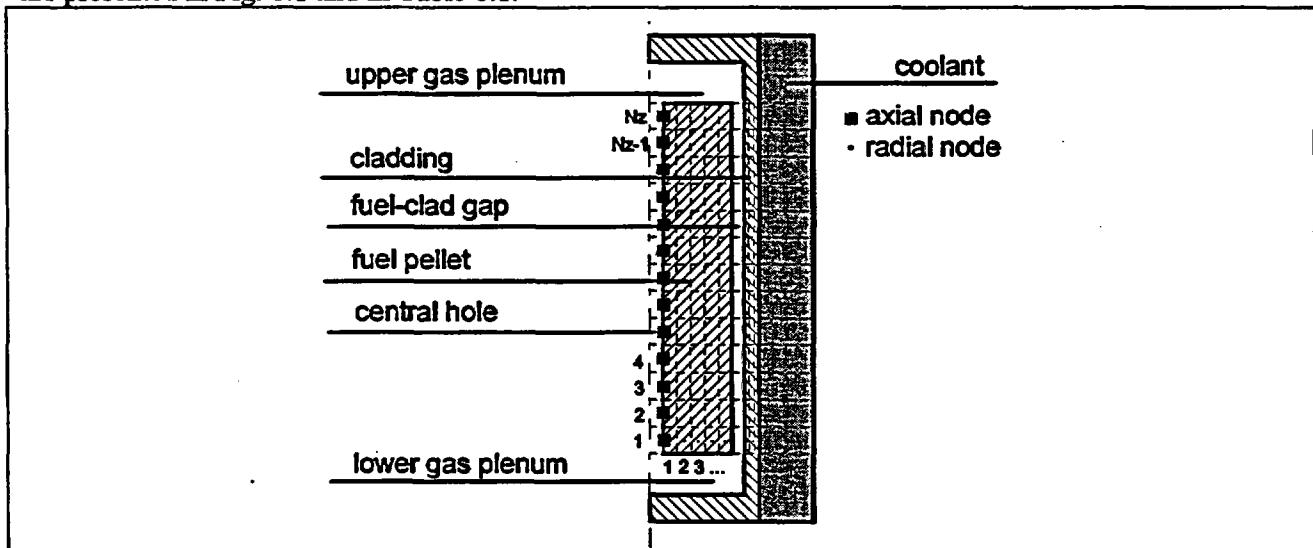


Fig. 8.1. Nodalization scheme.

Table 8.1. Main parameters of input data specification.

• axial nodes:	10
• radial nodes:	31, including:
fuel:	25
cladding:	6
• time step during fast transient:	$1 - 5 \cdot 10^{-3}$ s
• time step during slow transient:	$5 \cdot 10^{-3} - 1.0$ s
• parameters of numerical solution accuracy:	
fuel temperature	± 1 K
maximum number of iterations when calculating gas pressure and radial temperature distribution	200
relative difference between two iterations (criterion to stop calculations)	0.1 %

Change of the power parameters in the process of accident including fuel rod power, energy deposition in the fuel, fuel enthalpy, and leakage of heat from the cladding surface is presented in Fig. 8.2. Fig. 8.3 presents the change of temperature parameters and the coefficient of heat transfer from the cladding to the coolant. Fig. 8.4 presents the information on the change of gas pressure inside the fuel rod, and circumferential component of the loadings in the cladding in the process of the accident. Total hoop strain of the cladding and fuel, as well as the gas gap size are presented in Fig. 8.5. Change of gas release and fuel gas swelling versus time is presented in Fig. 8.6.

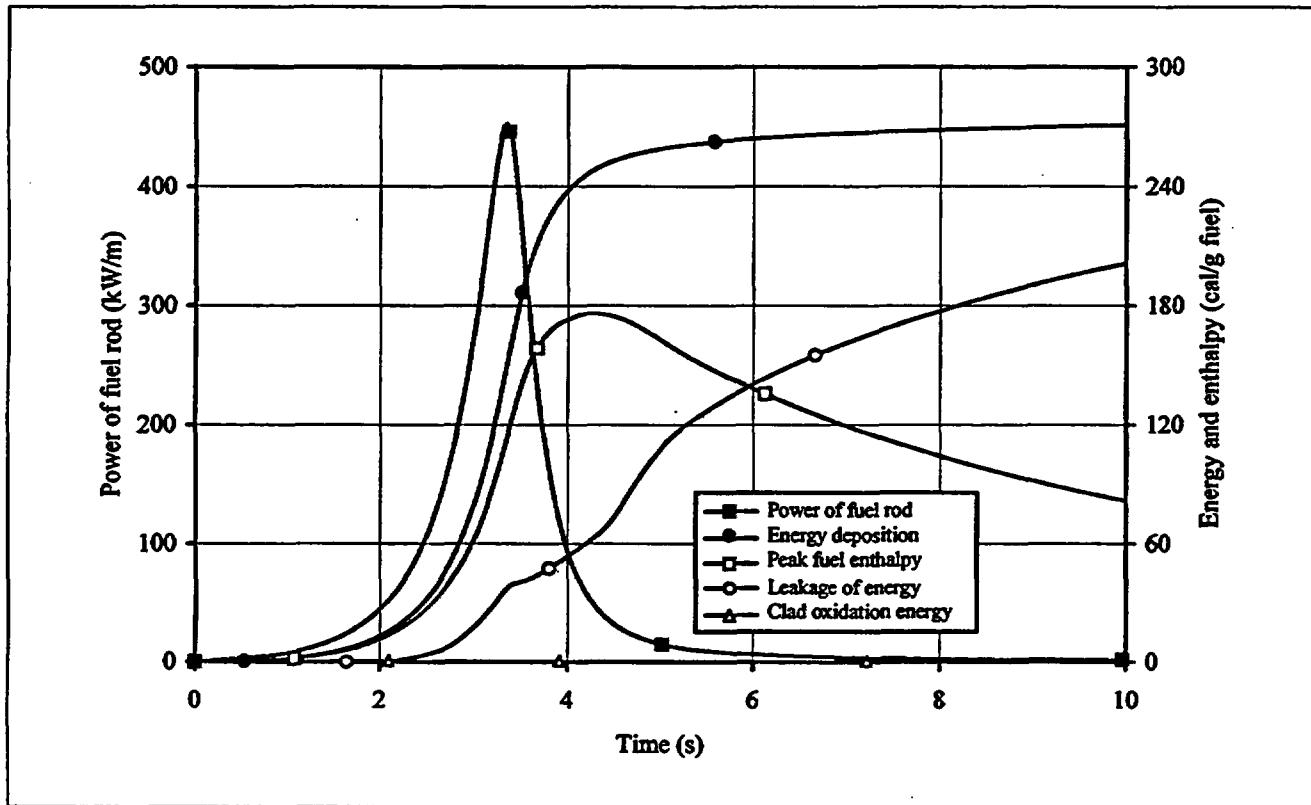


Fig. 8.2. Time history of fuel rod energy parameters in accident.

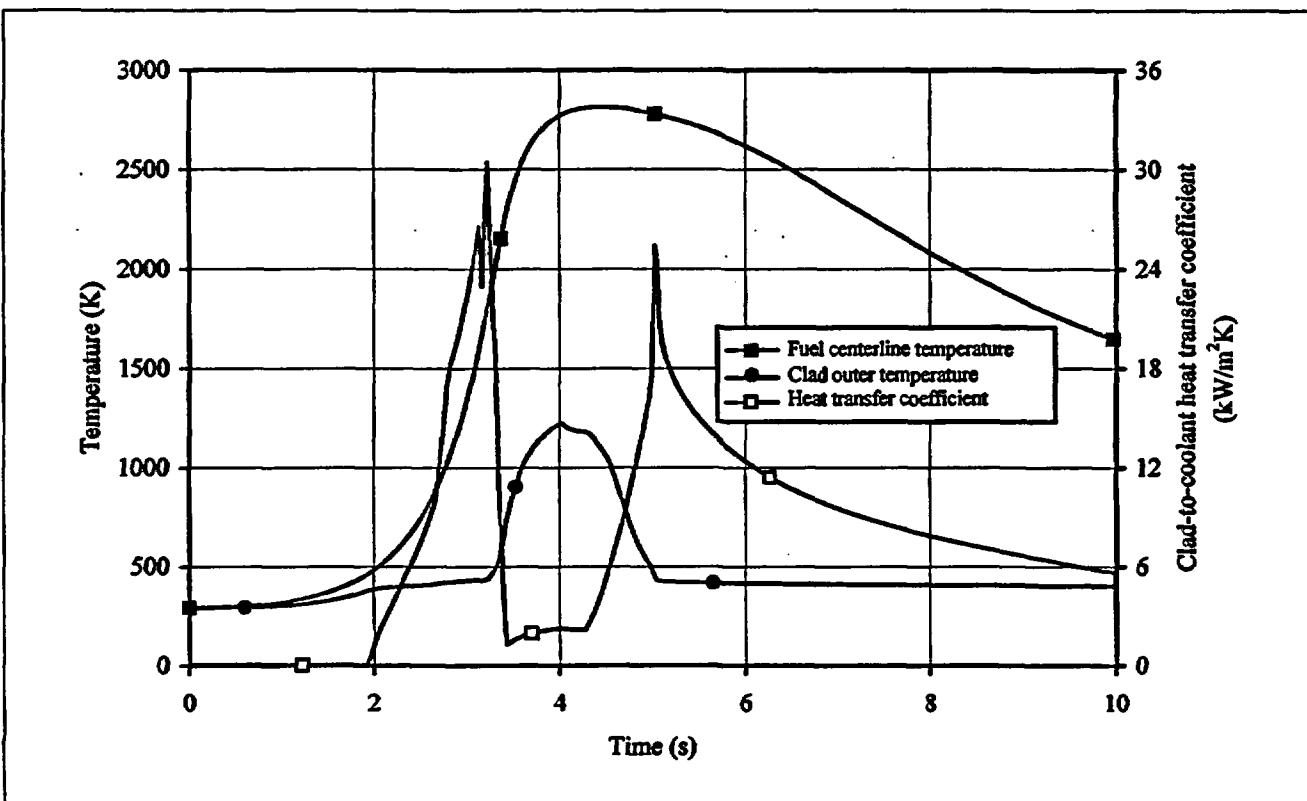


Fig. 8.3. Time history of fuel rod temperature parameters and clad-to-coolant heat transfer coefficient in accident.

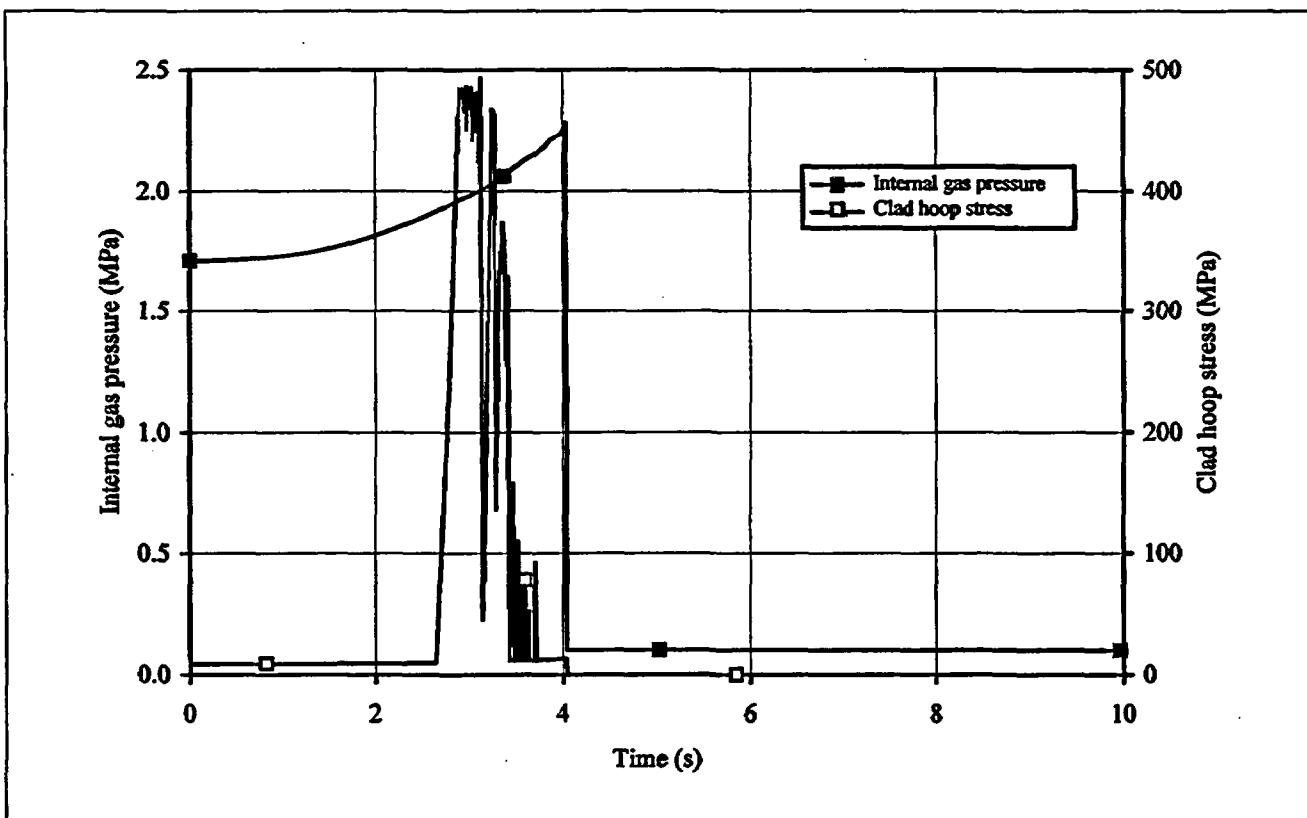


Fig. 8.4. Time history of inner gas pressure and clad hoop stress in accident.

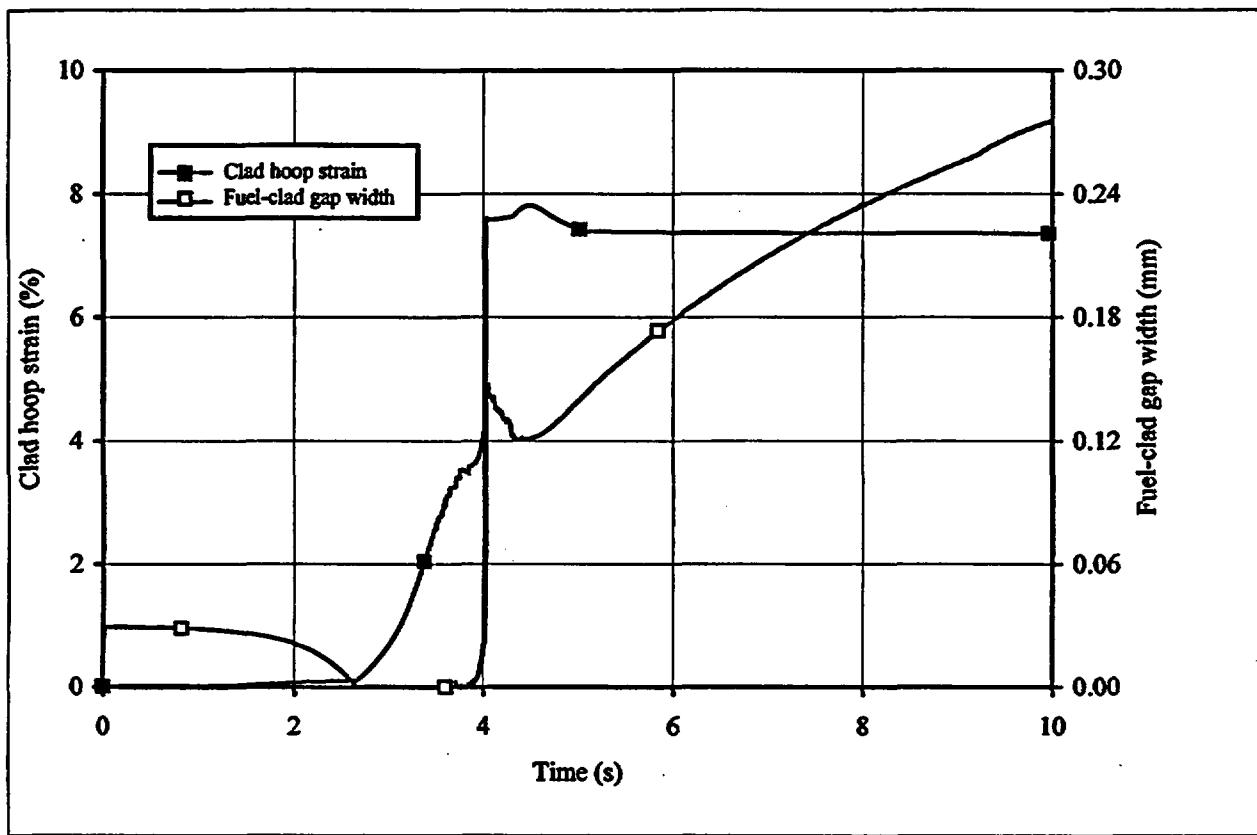


Fig. 8.5. Time history of total fuel and clad hoop strain and gas gap width in accident.

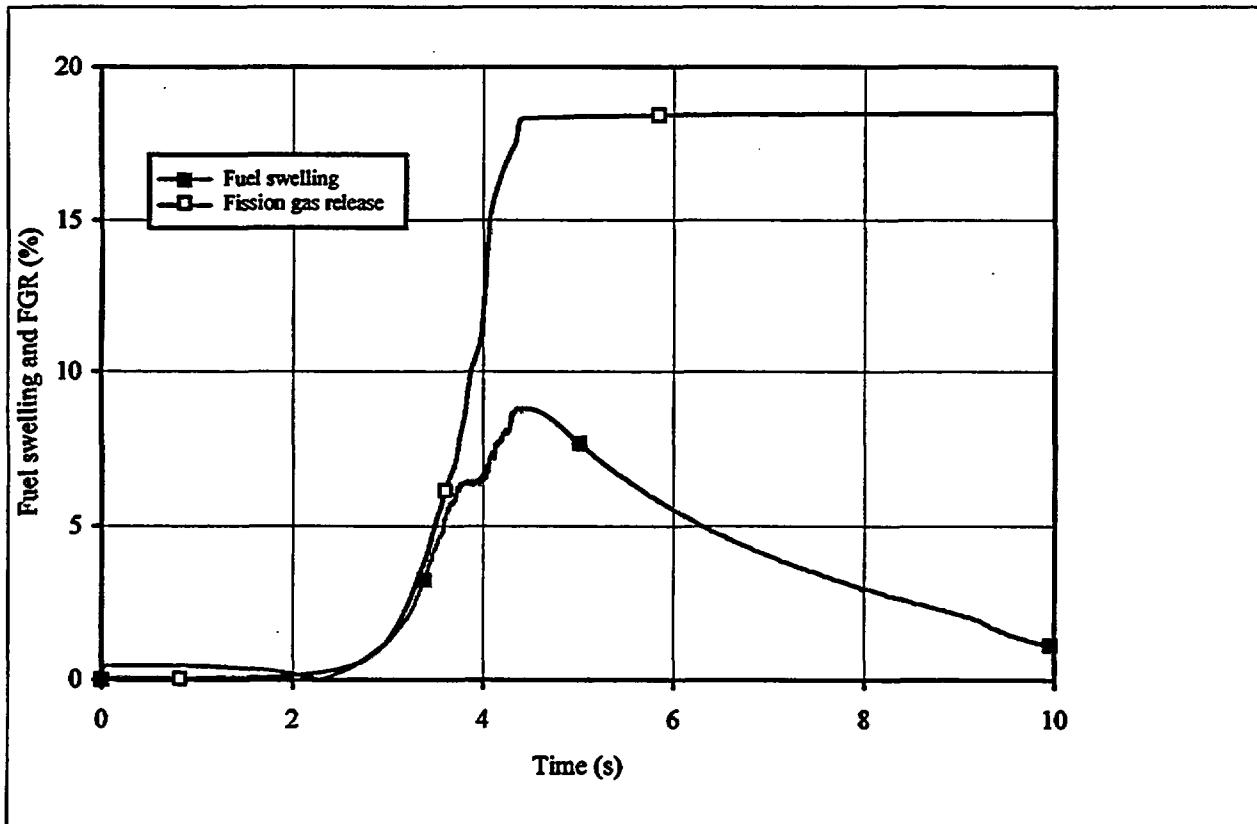


Fig. 8.6. Time history of fission gas release and fuel swelling.

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APPENDIX A. List of new and modified subroutines of FRAP-T6/VVER code

```

FUNCTION CCP (CTEMP)
C
C THIS BLOCK CALCULATES THE SPECIFIC HEAT AT CONSTANT PRESSURE FOR H1-ALLOY CLADDING.
C IF IWWER = 1 THEN DATA IS DERIVED FROM VOLKOV B.YU. ET. AL."MATERIAL PROPERTY
C LIBRARY FOR H1-ALLOY CLADDING", REPORT IAE-4941/11, 1989. THIS PROPERTY ARE
C INDUCED BY LOW HEATING RATE. IF IWWER = 2 THEN DATA IS DERIVED FROM LJUSTERNIK V.E.
C ET. AL."EXPERIMENTAL RESEARCH OF ZIRCONIUM REACTOR
C MATERIALS THERMAL PROPERTIES:110-ALLOY". M.,J. HIGH TEMPERATURE THERMAL PHYSICS."
C V.31 N.4, 1993. THIS PROPERTY ARE INDUCED BY HIGH-RATE HEATING>=1000 K/S.
C
C      ELSEIF(IWWER.EQ.1) THEN
C
C        IF(CTEMP.GE.1173.0D0) GO TO 3
C        CCP = POLATE(CPNWER,CTEMP,NPW,IU)
C        WRITE(0,*) 'LT 1173 ',CCP,CTEMP
C        RETURN
C        3      CCP = 392.D0
C        WRITE(0,*) 'GE 1173 ',CCP,CTEMP
C        RETURN
C
C      ELSE
C
C        IF IWWER=2
C
C        IF(CTEMP.LE.1100.) THEN
C          CCP = 237.5D0+15.91D-2*CTEMP
C        ELSEIF(CTEMP.LE.1200.) THEN
C          CCP = POLATE(CPWR2,CTEMP,NPW2,IU)
C        ELSE
C          CCP = 199.7D0+12.364D-2*CTEMP
C        ENDIF
C        WRITE(0,*) 'FINAL ',CCP,CTEMP
C
C      ENDIF
C
SUBROUTINE CTHEXP (CTEMP, CATHEX, CDTHEX)
  IF(IWWER.GT.0) THEN
    T=CTEMP
    IF(T.GE.2133.D0) THEN
      STRS11=1.0582459D-2
      STRS33=1.3133600D-2
      ZNDILA=(2.D0*STRS11+STRS33)/3.D0+0.0067D0
    C
    ELSE IF(T.GT.1153.D0) THEN
      STRS11=1.076459D-3+9.7D-6*(T-1153.D0)
      STRS33=3.627600D-3+9.7D-6*(T-1153.D0)
      ZNDILA=(2.D0*STRS11+STRS33)/3.D0
    C
    ELSE IF(T.GT.883.D0)THEN
      TT=T-883.D0
      STRS11=3.0465577D-3+2.312D-8*TT-7.358D-8*TT**2+1.7211D-10*TT**3
      STRS33=5.5977000D-3+2.312D-8*TT-7.358D-8*TT**2+1.7211D-10*TT**3
      ZNDILA=(2.D0*STRS11+STRS33)/3.D0
    C
    ELSE IF(T.GT. 573.D0) THEN
      STRS11=0.13725577D-2+5.4D-6*(T-573.D0)
      STRS33=0.3336985D-8*T**2+5.65390D-6*T-0.199649865D-2
      ZNDILA=(2.D0*STRS11+STRS33)/3.D0
    C
    ELSE
      STRS11=0.1338985D-8*T**2+3.85875D-6*T-0.127813365D-2
      STRS33=0.3336985D-8*T**2+5.65390D-6*T-0.199649865D-2
      ZNDILA=(2.D0*STRS11+STRS33)/3.D0
    C
    PRINT*, 'ZN',T,STRS11, STRS33
    C
    PRINT*, 'ZR',T,CATHEX, CDTHEX
  
```

```

        ENDIF
C
C      CDTHEX =STRS33
C      CATHEX =STRS11
C      ENDIF
C      <VVER<
C
C      CATHEX = CATHEX*DCEXP
C      CDTHEX = CDTHEX*DCEXP
C      RETURN
C      END

FUNCTION CELMOD (CTEMP, FNCK, CWKF, DELOXY)
C
C      FOR ZR-1&NB
C
IF(IWWR.GT.0) THEN
IF(CTEMP.LE. 1073.0D0) THEN
CELMOD = 1.121D11 - 6.438D07 * CTEMP
CELMOD = CELMOD + 3.021D12 * DELOXY
ELSEIF(CTEMP.LE. 2133.0D0) THEN
CELMOD = 9.129D10 - 4.5D07 * CTEMP
ELSE
CELMOD = 1.0D-10
ENDIF
ENDIF

SUBROUTINE CTHCON (CTEMP, TIME, FLUX, COLDW, CCON, CDKDT)
C
C THIS CODE BLOCK CALCULATES THERMAL CONDUCTIVITY (W/(M*K)) AND DERIVATIVE OF THERMAL
C CONDUCTIVITY WITH RESPECT TO TEMPERATURE (W/(M^K^2)) OF H1-ALLOY. DATA IS DERIVED
C FROM: C VOLKOV B.YU. ET. AL."MATERIAL PROPERTY LIBRARY FOR H1-ALLOY C CLADDING",
C REPORT IAE-4941/11, 1989.
C
100    CONTINUE
IF(CTEMP.LE.2133.0D0) THEN
CCON = EXP(0.000461843D0*CTEMP)*15.0636D0
CDKDT = 0.006957018215D0*EXP(0.000461843D0*CTEMP)
ELSE
CCON = 36.D0
CDKDT = 0.D0
ENDIF

FUNCTION CMHARD (CTEMP)
C
C FOR ZR-1&NB:
C
IF(IWWR.GT.0) THEN
IF(T.LE.773.D0) THEN
CMHARD=2172.1D0 - 10.7055*T+0.02765*T**2
* -3.278D-5*T**3 + 1.423D-8*T**4
ELSE
CMHARD=850.0D0 - 64.D0*T
ENDIF
ENDIF
CMHARD=CMHARD*1.D6

FUNCTION EMCPIR(CTEMP)
IMPLICIT REAL*8(A-H, O-Z)
INCLUDE 'WWR.H'
C
C FUNCTION COMPUTES POISSON'S RATIO
C T = CLADDING TEMPERATURE (KELVIN)
C
C THIS FUNCTION IS A CONVERSION TO KELVIN TEMPERATURES OF AN EXPRESSION RECOMMENDED
C FOR USE IN EVALUATION MODELS BY F.COFFMAN OF AEC-REGULATORY, APRIL 1974.
C CPOIR=.32+5.E-5*T (FAHRENHEIT)
        T = CTEMP
C
C      CPOIR = 0.32D0 + 5.D-5 * (T*1.8D0-459.67D0)

```

```

C      IF(IWWER.GT.0) CPOIR=0.333 - 0.000126*CTEMP
C
C      EMCPIR = CPOIR
C      RETURN
C      END

C
FUNCTION CCPINT(T1, T2)
IMPLICIT REAL*8 (A-H,O-Z)

C      CCPINT INTEGRATES THE FUNCTION CCP BETWEEN THE TEMPERATURE LIMITS
C      OF T1 AND T2
C      T1      = INPUT LOWER BOUND TEMPERATURE (K)
C      T2      = INPUT UPPER BOUND TEMPERATURE (K)
C      CCPINT = OUTPUT INTEGRAL OF CCP (J/KG)
C
C      INCLUDE 'WWER.H'
CANDR
COMMON/INDX/K111,K1111,K11111,ITRAN
COMMON /ANDREW/ CTHC11,CCPP11,FTHC11,FCPP11,CKMN11,CTHE11,FTHE11
*,FPO11,FQQ11,HTT11
C
DIMENSION CPI(32), CPW1(32), CPW2(32)
C
DATA CPI / 0.0D0, 290.D0, 2800.D0, 300.D0, 31950.D0, 400.D0,
# 107910.D0, 640.D0, 266760.D0, 1090.D0, 268075.D0, 1093.D0,
# 278995.D0, 1113.D0, 291045.D0, 1133.D0, 304385.D0, 1153.D0,
# 319735.D0, 1173.D0, 335595.D0, 1193.D0, 349485.D0, 1213.D0,
# 360365.D0, 1233.D0, 366553.D0, 1248.D0, 741062.D0, 2300.D0,
# 1.1683D+6 , 3500.D0/
C
DATA CPW1 / 0.0D0, 290.D0, 35195.D0, 400.D0, 70731.D0, 500.D0,
# 145246.D0, 700.D0, 214374.D0, 880.D0, 245414.D0, 940.D0,
# 285763.D0, 1000.D0, 325447.D0, 1050.D0, 370510.D0, 1113.D0,
# 390210.D0, 1153.D0, 408714.D0, 1200.D0, 428314.D0, 1250.D0,
# 447914.D0, 1300.D0, 467514.D0, 1350.D0, 839914.D0, 2300.D0,
# 1.3103D+6 , 3500.D0/
C
DATA CPW2 / 0.0D0, 290.D0, 33198.D0, 400.D0, 110054.D0, 640.D0,
# 181100.D0, 840.D0, 242520.D0, 1000.D0, 262549.D0, 1050.D0,
# 307641.D0, 1113.D0, 321956.D0, 1133.D0, 336271.D0, 1153.D0,
# 350586.D0, 1173.D0, 369911.D0, 1200.D0, 387469.D0, 1250.D0,
# 405336.D0, 1300.D0, 423512.D0, 1350.D0, 827588.D0, 2300.D0,
# 1.4975D+6 , 3500.D0/
C
DATA NCPI / 16 / , IV / 1 / , IY / 1 /
C
IF(IWWER.EQ.0) THEN
C
CPI1=POLATE( CPI, T1 , NCPI, IV )
CPI2=POLATE( CPI, T2 , NCPI, IY )
CCPINT=CPI2-CPI1
C
RETURN
C
C
THIS BLOCK CALCULATES THE ENTHALPY AT CONSTANT PRESSURE FOR
H1-ALLOY CLADDING. IF IWWER = 1 THEN DATA IS DERIVED FROM
VOLKOV B.YU. ET. AL."MATERIAL PROPERTY LIBRARY FOR H1-ALLOY
CLADDING", REPORT IAE-4941/11, 1989. THIS PROPERTY ARE INDUCED
BY LOW HEATING RATE. IF IWWER = 2 THEN DATA IS DERIVED FROM
LJUSTERNIK V.E. ET. AL."EXPERIMENTAL RESEARCH OF ZIRCONIUM REACTOR
MATERIALS THERMAL PROPERTIES:110-ALLOY". M.,J. HIGH TEMPERATURE
THERMAL PHYSICS." V.31 N.4, 1993. THIS PROPERTY ARE INDUCED BY
HIGH-RATE HEATING>=1000 K/S.
C
C
ELSEIF(IWWER.EQ.1) THEN
C
CPI1=POLATE( CPW1, T1 , NCPI, IV )
CPI2=POLATE( CPW1, T2 , NCPI, IV )

```

```

CCPINT=CPI2 - CPI1
C
C      RETURN
C
C      ELSE
C
C      CPI1=POLATE( CPW2, T1, NCPI, IV )
C      CPI2=POLATE( CPW2, T2, NCPI, IV )
C      CCPINT=CPI2 - CPI1
C
C      ENDIF
C
C      CCPINT=CCPP11*CCPINT
C      RETURN
C      END

SUBROUTINE PHYPRP
.

.

.

IF(IWWER.GT.0) FTMELT = 3110.15D0- 35.77D0*FBU/10000.

.

.

ZR-1%NB ALLOY
C
C      IF(IWWER.GT.0) THEN
CTMELT = 2133.15D0
CHEFUS = 21.0D+04
C
CC FOR SLOW HEAT RATE:
CTRANB = 883.D0
CTRANE = 1153.D0
CC FOR FAST HEAT RATE:
CTRANB = 1150.D0
CTRANE = 1200.D0
C
CTRANZ = 1135.15D0
ENDIF
C
C
CALL DIALOT(DELOXY,29,FDIALA,FDIALM)
CTRANB=(CTRANB+FDIALA)*FDIALM
CTRANE=(CTRANE+FDIALA)*FDIALM
CTRANZ=(CTRANZ+FDIALA)*FDIALM
RETURN
END

SUBROUTINE QDOT (A, B, CPP, CPG, CP, RF, RG, R,
1           G, X, HD, HF, HG, PR, QCRIT, QQ, TBULK, TS, TSAT, TSUR,
#   IH, J, L, TEMPCM, ZROXID, DH, AFLOW, DR, BETA,ELAPT)
.

.

.

C      COMPUTE FILM BOILING TERM
C
646 DTSAT=TSUR-TSAT
DTSAT1=DTSAT
IF(DTSAT1.LT.0.1D0)DTSAT1=0.1D0
HFB= 0.62D0* ((HD/AL)**0.172D0) *
# (((TRG**3)*(RG*(RF-RG)*(HG-HF)*GRAVC)/(HD*VSG*DTSAT1))**0.25D0)
ATB = 2.71828183D0* ((QCRIT-QVAPOR)/DTHSU -(0.96D0-ALPHA)*HTBHSU)
C
C      COMPUTE TRANSITION BOILING HTC
C
HTB = ATB*DEXP(-BTB*DTSAT)
***** SHEST
SCOEF=1.0D0
HTOT_SHEST=SCOEF* (HTB+HFB)

```

```

TKG_S=THCON(N2, (TSAT+TSUR)/2.D0, RG)
VSG_S=VISC(N2, (TSAT+TSUR)/2.D0, RG)
PROP(1)=(TBULK+459.67D0)/1.8D0
PROP(2)=PR*SIPR
***** WATER PROPERTIES
CALL STH2X3(THERMO, PROP, IT, ERR)
ALFA_S=0.25D0*(TKG_S**2.D0 * CPG * GRAVC * (RF-RG)
#                                     /(VSG_S/( RG)))**0.3333333D0
#
HVEDA=PROP(5)      ! SI
CONVER=0.00094845D0/2.2046D0
DH=HF-HVEDA*CONVER ! BTU
HVALI=HG-HF        ! BTU
ROLIQ=1.D0/PROP(3) ! SI
***** AT (TSUR+TSAT)/2=TFILM
PROP(1)=((TSUR+TSAT)/2.+459.67D0)/1.8D0
CALL STH2X3(THERMO, PROP, IT, ERR)

ROVAP=1.D0/PROP(3) ! [SI]
COEALF=(1.+0.1*(ROLIQ/ROVAP)**0.75*DHF/HVALI)
ALFA_S=ALFA_S*COEALF
***** FOR ALFA_S
QLIQ=(ALFA_S)*DTSAT
*****
T1200=1200*1.8 -460
T630=630*1.8 -460
T800=800*1.8 -460
COR1=LOG10(1.D0)
COR10=LOG10(30.D0)
TBEG=TIMEHTC
TEND=TIMEHTC + 0.7
CC(2)=TBEG
CC(1)= COR1
CC(4)=TEND
CC(3)= COR10
TCUR=TSUR
***** FIRST CORRECT
CORREC=1.
IF (ELAPT.GT. TBEG. AND. TBEG.GT.0.D0) THEN
CORREC=POLATE(CC,ELAPT,2,1)
CORREC=10***(CORREC)
ENDIF
***** SECOND CORRECT
IF (IREWET.EQ.0) CORREC=1.
QTOT= (QVAPOR + QLIQ)*CORREC

IF (KPRINT.EQ.1)
#WRITE(6,986) TSUR,HFB,HTB,DTHSU,HTBHSU,QLIQ
986 FORMAT(39H FOR LOW FLOW, LOW VOID FRACTION, TSUR=E10.4,5H HFB=,
# E10.4,5H HTB=E10.4,7H DTHSU=E10.4,8H HTBHSU=E10.4,
# 6H QLIQ=E10.4)

DTSAT1=DTSAT
C
C   FROM CONDUCTION EQUATION, A*TSUR + B = QTOT
C   SOLVE ABOVE EQUATION FOR NEW SURFACE TEMPERATURE
C
IF (DTSAT1.LT.0.1D0) DTSAT1=0.1D0
HTOT=QTOT/DTSAT1
.
.
.
RETURN
END

SUBROUTINE CKMN(CTEMP,DELOXY,FNCK,FNCN,CWKF,CWNF,RSTRAN,AK,AN,AM)
IMPLICIT REAL*8 (A-H,O-Z)
C VVER CLAD PROPERTIES INCLUDED
C CKMN CALCULATES PARAMETERS FOR THE CLADDING EQUATION OF STATE
C AS A FUNCTION OF TEMPERATURE, AVERAGE OXYGEN CONCENTRATION,
C FAST NEUTRON FLUENCE, AND COLD WORK.
.
.
```

```

200  CONTINUE
C VVER >>>>
C     CHANGE IRRADIATION FLAG HERE (0 = FRESH, 1= IRRADIATED) !!!
C             IRR=1
C
C     FIND AM (SAME AS ZRY AT STRAIN RATE > 0.01/S)
C     IF(T .LE. 730.D0) AM = 0.02D0
C
C             A = 20.63172161D0
C             B = - 0.07704552983D0
C             C = 9.504843067D-05
C             D = - 3.860960716D-08
C             IF(T .GT. 730.D0) AM = A + T*(B+ T*(C+ T*D))
C             IF(T .GE. 900.D0) AM = -6.47D-02 + T * 2.203D-04
C
C
C     FIND STRAIN HARDENING EXPONENT, AN
C FOR IRRADIATED
C             IF(IRR.EQ.0) GOTO 111
C
C             AN= 0.0054616+3.12237D-04*TX-0.668358D-06*TX**2
C             1      +0.430236D-09*TX**3
C             IF(T .GT. 752.37D0)
C             1 AN= -1.58974+0.0050059*TX-4.99134D-06*TX**2
C             2      +1.62978D-09*TX**3
C FOR FRESH+IRRAD
C             IF(T .GT. 854.72D0) GOTO 111
C             GOTO 112
C 111   AN= 0.0462842+0.000197952*TX-0.331487D-06*TX**2
C             1      +1.39133D-09*TX**3
C 112   IF(T .GT.1223.D0) AN=0.047
C
C
C     FIND STRENGTH COEFFICIENT, AK
C FOR FRESH
C             IF(IRR.EQ.1) GO TO 321
C
C             AK= ( 863.33 - T* 1.90882 + 0.00209374*T**2
C             1      - 9.91178D-07*T**3) * 1.D+06
C             IF(T .GT. 795.18D0)
C             1 AK = 1.08414D+10*EXP( - 0.00521825D+00 * T)
C             IF(T .GT. 926.62D0) GOTO 322
C
C FOR IRRAD
C 321   AK= ( 738.221+ T* 0.0395682 - 0.00100875*T**2
C             1      + 0.370178D-06*T**3) * 1.D+06
C             IF(T .GT. 749.45D0)
C             1 AK = 7.925089D+11*EXP( - 0.01028539D+00 * T)
C             IF(T .GT. 846.44D0)
C             1 AK = 1.08414D+10*EXP( - 0.00521825D+00 * T)
C             IF(T .GT. 926.62D0) GOTO 322
C
C FOR FRESH+IRRAD
C 322   AK = (396.363 - 0.334806*T)*1.D+6
C             IF(T .GT.1123.54D0) AK = (56.6424 - 0.0324407*T)*1.D+06
C
C VVER <<<<
C 300   CALL DIALOT(CTEMP,20,FDIALA,FDIALM)
C             AK=(AK+FDIALA)*FDIALM
C             RETURN
C** THIS PROGRAM VALID ON FTN4 AND FTN5 **
C             END
C
C             SUBROUTINE CMLIMT (CTEMP,DELOXY,FNCK,FNCN,CWKF,CWNF,CINWID,
C             # CINRAD,CDPRES,CAXRAD,CAXSTR,RSTRAN,DELTMP,STRNYT,STRNYE,
C             # STRNUE,STRNIE,STSRPT,STRRPE,CYLDST,CYLDSE,CULTSE,CRSTE,
C             # CBRSSST,CTSTRT)
C             IMPLICIT REAL*8 (A-H,O-Z)
C             VVER BURST STRESS INCLUDED
C             .
C             .

```

```

C VVER >>>>>
10    CONTINUE
C LOW TEMPERATURE DATA ARE NOT AVAILABLE, FAILURE EXPECTED ABOVE 973 K
    RATIO = 4.5D0
    CTSTRT = RATIO * AK
        IF(T.GE.973 )
    #    CTSTRT = EXP(-0.00952232 * T) * 2.99522D+012
        IF(T.GE.1176.44)
    #    CTSTRT = EXP(-0.00301426 * T) * 1.41537D+009

C VVER <<<<<
20    CONTINUE
C FIND UNCERTAINTY ESTIMATE FOR CTSTRT
C UCTSTT = 0.17D0* CTSTRT
C GO TO 321
C FIND TRUE TANGENTIAL FAILURE STRAIN FOR AZIMUTHALLY SYMMETRIC
C DEFORMATION
IF(CAXRAD .LT. 1.0D-03) CAXRAD = 1.0D-03
IF(CAXRAD .GT. 1.0D+01) CAXSTR = 0.0D0
AXFAC = CAXSTR*CINWID/(2.0D0* CDPRES*CAXRAD)
STSRPT = LOG((CTSTRT*CINWID/(CDPRES*CINRAD))**0.5D0+ AXFAC *
#           (1.0D0+ 0.5D0* AXFAC) )

C FIND TYPICAL CIRCUMFERENTIAL ENGINEERING STRAIN AT RUPTURE
STRRPE = ((CTSTRT*CINWID/(CDPRES*CINRAD))**0.5D0- 1.0D0) *
#           EXP(-0.01D0* DELTMR)
C* DELETE RUPTURE STRAIN LIMIT OF 0.05 IN CMLIMT
C FIND EFFECTIVE TRUE TANGENTIAL STRESS AT BURST FOR IDEALIZED
C SYMMETRIC DEFORMATION AND TYPICAL CIRCUMFERENTIAL STRAIN
C FIND TYPICAL CIRCUMFERENTIAL ENGINEERING STRAIN AT INSTABILITY
STRNIE = ((AK * CINWID * (10.D0**2.0D0*AM)) / (CDPRES * CINRAD
#           * (0.866D0**1.0D0+ AM + AN)))**0.5D0- 1.0D0)

IF(STRNIE .LT. .05D0) STRNIE = .05D0
IF(STRNIE.GT.0.5D0) STRNIE=.5D0

IF(STRRPE.LT.STRNIE) STRRPE=STRNIE
CBRSST=(CDPRES *CINRAD / CINWID)*((1.0D0+ STRRPE)**2 )
STRNIE = STRNIE * EXP(-0.01D0* DELTMR)

C FIND TYPICAL ENGINEERING HOOP STRESS AT BURST
FT      = (CTEMP - 273.15D0) * 1.8D0+ 32.D0
CRSTE = (10**5.00D+00+FT*(3.27D-04-FT*(1.14D-06-FT*2.56D-10)))/
#           1.4505D-04
CALL DIALOT(CTEMP,21,FDIALA,FDIALM)
    STSRPT=(STSRPT+FDIALA)*FDIALM
    RETURN
C** THIS PROGRAM VALID ON FTN4 AND FTN5 **
END

```

SUBROUTINE HTRC(ACOND, A, B, DR, HTC, QQ, QCRIT, TSUR,
1 IHTREG, LHTC, IDEBUG, NQCHN,
2 KAXN, NSW, ELEV, RL, ICWF, PFACA, SHFRV, FQCRIT, NCHFSW,
3 NCHEMD, TEMPCM, ZROXID, TMELTC, ELAPTM)

C ***** SHEET 10-OCT-95 INSERT AIR COOLANT CONDITIONS *****
C COMPUTE HEAT TRANSFER COEFFICIENT ASSUMING HELIUM OR AIR FLOWING PAST
C CLADDING SURFACE. WARNING !
* HELIUM HTC FOR FORCED CONVECTION
* AIR HTC FOR FREE CONVECTION
C*****
C
C TCON = THERMAL CONDUCTIVITY OF HELIUM (BTU/FT-HR-F)
C TVIS = DYNAMIC VISCOSITY OF HELIUM (LBM/HR-FT)
C
C

3000 CONTINUE

```

      IF (JCHF.EQ.10) THEN
*     SHEST IMPLEMENTATION 10-OCT-95 - AIR FREE CONVECTION MODEL:
*     KIRILLOV P.L. YURJEV YU.I., BOBKOV V.P.
*     "THERMOHYDRAULIC ANALYSIS HANDBOOK" M., ENERGOATOMIZDAT., 1990
C
***** CONVERT TEMPERATURE FROM F TO K
C     IF (ELAPTM.LE.0.0D0) THEN
      TTN=(TBULK +459.69D0) / 1.8D0
      TW =(TBULK+1. +459.69D0) / 1.8D0
      IF (ELAPTM.LE.0.0D0) THEN
        TAIR_CL=TTN+1.
        TSUR=(TAIR_CL * 1.8D0) -459.69D0 ! TAIR_CL IN K, TSUR IN F
      ELSE
        TAIR_CL=(TSUR+459.69D0) / 1.8D0
        IF (TSUR.LE.TBULK) TSUR=TBULK+1.
      ENDIF
      TSH=((TAIR_CL+TTN)*0.5D0)-273.D0
      BETAV=0.0332D0
      GFF=9.8066D0
      ZED=RL*0.3048D0
*****
      ALAM = THERMAL CONDUCTIVITY OF AIR [W/M K] *****
      ALAM=
      *   (24.407D0 + 7.978D-2*(TSH)
      *   - 3.154D-5*(TSH)**2 + .802D-8*(TSH)**3)*1.D-3
*****
      CPAIR = SPECIFIC HEAT OF AIR [J/(KG K)] *****
      CPAIR=1004.16D0-9.761D-3*TSH+55.229D-5*TSH**2 - 36.275D-8*TSH**3
*****
      ATEMP = TEMPERATURE CONDUCTIVITY OF AIR [M2/S] *****
      ATEMP=
      *   (18.788D0 + 13.484D-2*(TSH) + 13.959D-5*(TSH)**2
      *   - 4.654D-8*(TSH)**3)*1.D-6
*****
      AMU = DYNAMIC VISCOSITY OF AIR [PA/S] *****
      AMU=(17.162D0 + 49.894D-3*(TSH) - 2.935D-5*(TSH)**2
      * +1.133D-8*(TSH)**3)*1.D-6
*****
      DENS = AIR DENSITY [KG/M3] *****
      DENS=
      * -2.883D-3 + 355.06D0/(TSH+273.D0) + 353.527D0/(TSH+273.D0)**2
      DENS2=
      * -2.883D-3 + 355.06D0/(TTN) + 353.527D0/(TTN)**2
      VI=(AMU/ 1.0D0)/DENS2 ! KOSTIK ALLOWS TO DELETE "GFF"
      T_RA=(TSUR+459.69D0)/1.8D0 ! TSUR [F], T_RA [K]
CCC      RA=(GFF*BETAV*(T_RA-TTN)*ZED**3)/(VI*ATEMP)
      RA=(GFF*(DENS2-DENS)*ZED**3)/(AMU*ATEMP)
      RA = AMAX1(RA,1.D-12)
      PR=VI/ATEMP
      APR=LOG10(PR)
      IF(APR.LE. -0.1D0) APR=-0.1D0
      IF(APR.GE. 2.D0) APR= 2.0D0
      CSH=POLATE(CC,APR,4,1)
      DEG=0.25D0
C KON
      IF(RA.LT.1.D+9) THEN
        CSH=0.59
        DEG=0.25
      ELSE IF(RA.LT.1.D+13) THEN
        CSH=0.021
        DEG=0.4
      ELSE
        CSH=0.1
        DEG=0.33
      ENDIF
      ANUSS=CSH*(RA**DEG) ! /1.10D0
C
C     HTC = CALCULATED HEAT TRANSFER COEFFICIENT (W/M2-K)
C
C     HTC_SI=ALAM*ANUSS/ZED !* AC_PL
C
C     COMPUTE RADIATION HTC
C
      ALPHA=1.0D0 ! VOID FRACTION FOR GAS COOLANT
      CALL EMSSF1(TEMPCM, ALPHA, ZROXID, FE) ! FOR CLAD-TO-VAPOUR RAD
C
C     ASSUME CONFIGURATION FACTOR EQUALS ONE
C
      FE=0.4D0

```

```

      IF (ABS(T_RA-TTN).LE.1.-3) T_RA=TTN+0.1
CCCCC FOR HTC=1.20     HRAD=FE*5.67D-8* ( T_RA**4 - TTN**4)/(T_RA - TTN)
C           HRAD=1.30548D-8* ( T_RA**4 - TTN**4)/(T_RA - TTN) !*1.5
C
C           CONVERT HTC FROM (W/M2-K) TO (BTU/HR-FT2-F)
C           T FROM K TO F
C           HF FROM (W/M2) TO (BTU/HR-FT2)
C
HTC=(HTC_SI+HRAD)/5.67826334D0
IF (KREAL.EQ.1MAX1) THEN
    HTCC=HTC*5.67826334D0
    HTC_COOL=HTC_SI
    HRADD=HRAD
ENDIF
TW = (BB+HTC*T BULK)/(HTC-AA)
QQ = HTC*(TW-T BULK)
TSUR=TW
ELSE
    IF( NHEL.EQ.0) THEN
        WRITE(0,*)'
        WRITE(0,*)'*****WARNING !*****
        WRITE(0,*)'* HELIUM IS USED AS A COOLANT *
        IF(JCHF.EQ.9)
        * WRITE(0,*)'* AIR IS USED AS A COOLANT *
        * WRITE(0,*)'* (FORCED CONVECTION MODEL) *
        WRITE(0,*)'* ("HTRC" SUBCODE) *
        WRITE(0,*)'*****'
        WRITE(0,*)'NHEL=1
ENDIF

IF (JCHF.EQ.11) THEN
***** CONVERT TEMPERATURE FROM F TO K FOR AIR FORCED CONVECTION
TTN=(T BULK +459.69D0) / 1.8D0
TW =(T BULK +459.69D0) / 1.8D0

TSH=TTN-273.D0

***** ALAM = THERMAL CONDUCTIVITY OF AIR [W/M K] *****
ALAM=
*(24.407D0 + 7.978D-2*TSH - 3.154D-5*TSH**2 + .802D-8*TSH**3)*1.D-3

***** CPAIR = SPECIFIC HEAT OF AIR [J/(KG-K)] *****
CPAIR=1004.16D0-9.761D-3*TSH+55.229D-5*TSH**2 - 36.275D-8*TSH**3

***** ATEMP = (A) - TEMPERATURE CONDUCTIVITY OF AIR [M2/S] *****
ATEMP= (18.788D0 + 13.484D-2*TSH + 13.959D-5*TSH**2
* - 4.654D-8*TSH**3)*1.D-6

***** AMU = DYNAMIC VISCOSITY OF AIR [PA/S] *****
AMU=(17.162D0 + 49.894D-3*TSH - 2.935D-5*TSH**2
* +1.133D-8*TSH**3)*1.D-6
***** DENS = AIR DENSITY [KG/M3] *****
DENS=
* -2.883D-3 + 355.06D0/(TSH+273.D0) + 353.527D0/(TSH+273.D0)**2

PRSI=6.897D+3 * PR
TEMPK=(T BULK+459.69D0)/1.8D0
GPTHK=0.D0
CPHE=CPAIR/4186.D0
TCON=ALAM*0.577902D0
TVIS=(AMU/9.8066D0)*2419.09D0

ELSE
***** FOR H E L I U M *****
C
C***** CPHE = SPECIFIC HEAT OF HELIUM [BTU/(LBM-F)]
C
CPHE = 1.24D0
PRSI=6.897D+3 * PR

```

```

TEMPK=(TBULK+459.69D0)/1.8D0
GPTHK=0.D0
TCON = 0.577902D0*GTHCON(GMIX, TEMPK, PRSI, GPTHK)
TVIS = 2419.09D0*GVISCO(GMIX, TEMPK)

        ENDIF
C      RE = REYNOLDS NUMBER
C      RE=G*HD/TVIS
C      PRN = PRANDTL NUMBER
C      PRN = CPHE*TVIS/TCON

C      FNU = NUSSELT NUMBER
C      ANU = 0.0215D0
C      ENU = 1.15D0
C      CNU = 0.8D0
C      DNU = 0.6D0
C      FNU=ANU*ENU* (RE**CNU)*(PRN**DNU)
C      HTC = CALCULATED HEAT TRANSFER COEFFICIENT (BTU/HR-FT2-F)
C      IF(TSUR.GT.(TSAT+250.D0))GO TO 651
C      HRAD=0.0D0
C      GO TO 655
651      CONTINUE
C      COMPUTE RADIATION HTC

C      CALL EMSSF1(TEMPCM, ALPHA, ZROXID, FE)
C      ASSUME CONFIGURATION FACTOR EQUALS ONE
C      WRITE(0,*) ELAPTM, TSUR, TBULK
C      IF(ELAPTM.EQ.0.0D0) TSUR=TBULK+1.
C      WRITE(0,*) ELAPTM, TSUR, TBULK

HRAD=FE*SIGMA* (( TSUR + FTOR)**4 - (TBULK + FTOR)**4)/
*(TSUR - TBULK) !* AC_PL

655      CONTINUE

IF(Z.GT.ZROUG1.AND.Z.LT.ZROUG2) FNU=2.D0*FNU
HTC_C=FNU*TCON/HD !* AC_PL
HTC=(HTC_C + HRAD)
IF(KREAL.EQ.LMAX1) THEN
HTCC=HTC*5.67826334D0
HTC_COOL=HTC_C*5.67826334D0
HRADD=HRAD*5.67826334D0
ENDIF
C
TSUR=(BB+HTC*TBULK)/(HTC-AA)
QQ=HTC*(TSUR-TBULK)

ENDIF

IF(JCHF.EQ. 9) IHTREG= 90
IF(JCHF.EQ.10) IHTREG=100
IF(JCHF.EQ.11) IHTREG=110
QCRIT=0.0D0

RETURN

C      CALL THE EVALUATION MODEL HTRC AND COMPANION QDOT
722  CONTINUE
        CALL EMHTRC (ACOND ,A      ,B      ,DR      ,HTC      ,QQ      ,QCRIT ,
1          TSUR   ,IHTREG,LHTC   ,IDEBUG,NQCHN ,KAXN   ,NSW      ,
2          ELEV   ,RL     ,ICWF   ,PFACA  ,SHFRV   )

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```

        PRINT*, 'FROM HTRC', QCRIT
950  CONTINUE
      RETURN
      END

      SUBROUTINE RIMMOD (PRAD,NPRAD)
C
C     BUFACT - AVERAGE BURNUP, MWD/KG
C
C     IMPLICIT REAL*8 (A-H,O-Z)
C     INCLUDE 'WWER.H'
C     PARAMETER( NPOI=23, NBUR=3 )
C     DIMENSION PRAD(50)
C
C     DIMENSION PRADIN(NBUR,NPOI)
C     DIMENSION WORK1(NBUR), WORK2(NPOI)
C     DIMENSION BUREF(NBUR)
C
C     DATA BUREF/ 0.D0, 50.D0, 100.D0/
C
C     DATA PRADIN/
C     *      1.000 ,1.000,   1.000,
C     *      1.000, 1.000,   1.000,
C     *      1.0,   1.0000,  1.0000,
C     *      1.0,   1.0000,  1.0000
C     * /
C
C     DATA PRADIN/
C     *      1.00E-9, 1.E-9,   1.E-9,
C     *      1.00E-9, 1.E-9,   1.E-9,
C     *      1.000, 0.8820,  0.8820,
C     *      1.000, 0.8820,  0.8820,
C     *      1.000, 0.9573,  0.9573,
C     *      1.000, 0.9573,  0.9573,
C     *      1.000, 1.2000,  1.2000,
C     *      1.000, 1.2000,  1.2000,
C     *      1.000, 1.8380,  1.8380,
C     *      1.000, 1.8380,  1.8380
C     * /
C
C     DATA PRADIN/
C     *      0.9583,0.9583,0.9583,
C     *      0.9583,0.9583,0.9583,
C     *      0.9583,0.9583,0.9583,
C     *      0.9583,0.9583,0.9583,
C     *      0.9773,0.9773,0.9773,
C     *      0.9773,0.9773,0.9773,
C     *      1.008, 1.008, 1.008,
C     *      1.008, 1.008, 1.008,
C     *      1.057, 1.057, 1.057,
C     *      1.057, 1.057, 1.057
C     * /
C
C     DATA PRADIN/
C     *      1. , 0.8820,  0.8820,
C     *      1. , 0.9573,  0.9573,
C     *      1. , 0.9573,  0.9573,
C     *      1. , 1.2000,  1.2000,
C     *      1. , 1.2000,  1.2000,
C     *      1. , 1.8380,  1.8380,
C     *      1. , 1.8380,  1.8380
C     * /
CCCCCCCCCCCCCCCCCCC FOR 5-NV-NPP (STEADY-STATE) (23 STRINGS)

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```

      DATA PRADIN/
      *      1.0E-9 , 1.0E-9 , 1.0E-9 ,
      *      1.0E-9 , 1.0E-9 , 1.0E-9 ,
      *      1.0E-9 , 1.0E-9 , 1.0E-9 ,
      *      1. , 0.88235 , 0.88235 ,
      *      1. , 0.88235 , 0.88235 ,
      *      1. , 0.88235 , 0.88235 ,
      *      1. , 0.88235 , 0.88235 ,
      *      1. , 0.88529 , 0.88529 ,
      *      1. , 0.89116 , 0.89116 ,
      *      1. , 0.89703 , 0.89703 ,
      *      1. , 0.90291 , 0.90291 ,
      *      1. , 0.90878 , 0.90878 ,
      *      1. , 0.91465 , 0.91465 ,
      *      1. , 0.92053 , 0.92053 ,
      *      1. , 0.92640 , 0.92640 ,
      *      1. , 0.94062 , 0.94062 ,
      *      1. , 0.96319 , 0.96319 ,
      *      1. , 0.98576 , 0.98576 ,
      *      1. , 1.00833 , 1.00833 ,
      *      1. , 1.03091 , 1.03091 ,
      *      1. , 1.12775 , 1.12775 ,
      *      1. , 1.29887 , 1.29887 ,
      CCC   *      1. , 2.86840 , 1.86840
      *      1. , 3.86840 , 1.86840
      * /
***** FROM TOSUREP
C      DATA PRADIN/
C      *      1.0E-9 , 1.0E-9 , 1.0E-9 ,
C      *      1.0E-9 , 1.0E-9 , 1.0E-9 ,
C      *      1.0E-9 , 1.0E-9 , 1.0E-9 ,
C      *      1.000 , 0.83554 , 0.83554 ,
C      *      1.0000 , 0.83554 , 0.83554 ,
C      *      1.0000 , 0.83554 , 0.83554 ,
C      *      1. , 0.83878 , 0.83878 ,
C      *      1. , 0.84526 , 0.84526 ,
C      *      1. , 0.85173 , 0.85173 ,
C      *      1. , 0.85821 , 0.85821 ,
C      *      1. , 0.86469 , 0.86469 ,
C      *      1. , 0.87117 , 0.87117 ,
C      *      1. , 0.87764 , 0.87764 ,
C      *      1. , 0.88412 , 0.88412 ,
C      *      1. , 0.90385 , 0.90385 ,
C      *      1. , 0.93683 , 0.93683 ,
C      *      1. , 0.96981 , 0.96981 ,
C      *      1. , 1.00279 , 1.00279 ,
C      *      1. , 1.03578 , 1.03578 ,
C      *      1. , 1.17907 , 1.17907 ,
C      *      1. , 1.43267 , 1.43267 ,
C      *      1. , 2.30544 , 2.30544
C      * /
      SAVE BUOLD, NKAL
C
      BUAUT = BURNTOT
      WRITE(6,*) 'RIMTIM* BURNUP', BUOLD, BUAUT
C
C -----
C CASE 1 : ARRAY SIZE MISMATCH
C
      IF(IRIM.EQ.0) THEN
        WRITE(*,*) 'RIMTIM IS USED IF BURNUP > 0'
        WRITE(*,*) 'RIMTIM POINTS', NPOI, NPRAD
        IRIM=IRIM+1
      ENDIF
      IF( NPOI.NE.NPRAD ) THEN
        WRITE(6,*) 'RIMTIM* CHECK NUMBER OF POINTS FOR PROFILES'
        WRITE(*,*) 'RIMTIM* CHECK NUMBER OF POINTS FOR PROFILES'
        STOP
      ENDIF
C -----
C CASE 2 : TEST FOR REPEATED CALL WITH THE SAME BURNUP - NO ACTION
C

```

```

        IF( NKAL.EQ.-1 ) THEN
          IF( BUACT.EQ.BUOLD ) THEN
C           WRITE(6,*) ' *RIMTIM* NO UPDATE OF PROFILE'
C           WRITE(*,*) ' *RIMTIM* NO UPDATE OF PROFILE'
            RETURN
          ENDIF
        ELSE
          NKAL=-1
        ENDIF
C
C -----
C CASE 3 : NEW BURNUP VALUE,
C           FIND ACTUAL PROFILE BY LINEAR INTERPOLATION IN PRADIN
C
        DO NP = 1,NPRAD
          KK = 0
          DO NB = 1,NEUR
            KK = KK + 1
            WORK1(KK) = PRADIN(NB,NP)
          ENDDO
          AA      = FINT(NBUR,BUREF,WORK1,BUACT)
C           WRITE(6,*) 'NP,BUACT,AA', NP,BUACT,AA
          WORK2(NP) = AA
        ENDDO
C
        NP    = 0
        NPR2 = NPRAD*2
C           WRITE(6,*) 'NPRAD,NPR2', NPRAD,NPR2
        DO II=1,NPR2,2
          NP = NP + 1
C           WRITE(6,*) II,PRAD(II),NP,WORK2(NP)
          PRAD(II) = WORK2(NP)
        ENDDO
C
C           WRITE(6,*) ' PRAD'
C           DO I=1,NPR2,2
C             WRITE(6,*) I, PRAD(I),PRAD(I+1)
C           ENDDO
C-----
        BUOLD = BUACT
C
        RETURN
      END

```

```

DOUBLE PRECISION FUNCTION FINT( NT,A,B,X )
IMPLICIT REAL*8(A-H,O-Z)
DIMENSION A(1),B(1)
C
  IF( X.LT.A(1) .OR. X.GT.A(NT) ) THEN
    WRITE(6,*) ' *RIMTIM* ERROR : BURNUP OUT OF RANGE'
    STOP
  END IF
C
  DO 1 I=1,NT
    XXX= X-A(I)
    IF( XXX.EQ.0.D0) THEN
      FINT=B(I)
      RETURN
    END IF
    IF( X.GT.A(I) .AND. X.LT.A(I+1) ) THEN
      FINT= B(I) + ( B(I+1)-B(I) )/( A(I+1)-A(I) ) * XXX
      RETURN
    END IF
  1  CONTINUE
END

```

```

SUBROUTINE RIMTIM
IMPLICIT REAL*8 (A-H,O-Z)
.
```

```

C+PF
C      VALUES SAVED IN 'COMINP'
C      DIMENSION RADNOD(100)
C      INCLUDE 'SAVEPF.H'
C      INCLUDE 'WWER.H'
C-PF
.
.
.
C+PF
C      SKIP EVERYTHING EXCEPT POWER
GOTO 7777
C-PF
.
.
.
C+PF-----
C      START ONLY HERE
7777 CONTINUE
C
C      MODIFY 'PRAD'
C
CALL RIMMOD(PRAD,NPRAD)
C
C-PF-----
.
.
.
C+PF
C      SKIP TO RADIAL POWER
GOTO 8888
C-PF
.
.
.
C+PF
C      CONTINUE HERE
8888 CONTINUE
C      RESTORE INDEXES SAVED IN 'COMINP'
HINDEX= HIN_S
NN     = NN_S
LMAX   = LMAX_S
C-PF
.
.
.
C+PF
C      WRITE(6,*) ' RIM-ARRAY',L,A1(INDEX1)
DO IZ=1,NAXN
C          PRINT*, 'RIMTIM', COEFPow(IZ,L)
COEFPow(IZ,L)=A1(INDEX1)
ENDDO
C-PF
.
.
.
C+PF
C      ENOUGH !
RETURN
C-PF

```

SUBROUTINE BURNUP(CON,CONBU,TEMP,BN)

```

C
C      THIS SUBCODE CALCULATES THERMAL CONDUCTIVITY VS. BURNUP
C      FOR PWR FUEL
C
IMPLICIT REAL*8 (A-H,O-Z)
INCLUDE 'WWER.H'
DIMENSION ALAM473(8),ALAM2973(8)
DATA ALAM473 / 1.00D0, 0.00D0,
*                 0.73D0, 30.0D0,
*                 0.55D0, 60.0D0,
*                 0.35D0, 100.0D0/

```

```

        DATA ALAM2973/ 1.00D0, 0.00D0,
        *          0.94D0, 30.0D0,
        *          0.89D0, 60.0D0,
        *          0.84D0, 100.0D0/

C     DATA ALAM473 / 1.00D0, 0.00D0,
C     *          1.00D0, 30.0D0,
C     *          1.00D0, 60.0D0/
C     DATA ALAM2973/ 1.00D0, 0.00D0,
C     *          1.00D0, 30.0D0,
C     *          1.00D0, 60.0D0/

TBEGIN=473.D0
TEND=1800.D0

BU_Z=BN/86400.D0

IF (BU_Z.GE.100.D0) BU_Z=100.D0
IF (TEMP.LE.TBEGIN) TEMP=BEGIN
IF (TEMP.GE.TEND) TEMP=TEND

ACOEF1=POLATE(ALAM473, BU_Z, 4,1)
ACOEF2=POLATE(ALAM2973,BU_Z,4,1)

CT=1.D0+(ACOEF2-ACOEF1)*(TEMP-TBEGIN)/(ACOEF1*(TEND-TBEGIN))
AX=ACOEF1*CT
CON0=CON
CONBU=CON0*AX
CONBU0=CONBU

***** DEGRADATION FROM PIN
C     BB=BU_Z/9.375D0
C     AB=(0.053+2.2D-4*T)/(0.053+0.016D0*BB+(2.2D0-0.005D0*BB)*T*1.D-4)
C
C     ABG=1.-AMIN1(0.05D0,BU_Z/600.D0)
C
C     IF( (T-273.D0) .GT. 1500.D0) THEN
C       B= 0.5D0
C     ELSE
C       B=4.4D0-1.6D0*(T-273.D0)/500 + 0.1D0*((T-273.D0)/500)**2
C     ENDIF
C     ABG=1.D0-0.001D0*B*BU_Z
C
C     CONBU=CON*AB*ABG
*****
CCC      PRINT*,AX,TEMP,BU_Z
        IF(AX .GT. 1.D0 .OR. AX .LT. 0.3 D0) THEN
PAUSE'FROM FTHCON: TOO LARGE/SMALL BURNUP FACTOR FOR CONDUCTIVITY'
        ENDIF

        RETURN
        END

FUNCTION TCOR (D,T,IMOD,BUR,COND)
IMPLICIT DOUBLE PRECISION (A-H,O-Z)
TT=T
C     SHEST INSERT DOMESTIC FUEL CONDUCTIVITY
IF(IMOD.EQ.1) TCOR=

C           PIN (RES MECCHANICA 16(1985) 25-63)
C           +(1./(0.0213*TT+8.77))
C           F=D/((1.+9.34068*(1-D)-9.5742*(1.-D)**2)*0.6583)
C           TCOR=TCOR*F
C           IF(TT.GE.1673.) TCOR=0.0253*F

C           PIN (RES MECCHANICA 16(1985) 25-63)
C           +(38.24/(TT+129.4)+6.1256E-13*TT**3)
C           +    *((1.025/.95)*(D/(1.+(1.-D)*.5)))
C           PRINT *,TCOR
+
+(1./(0.0258*TT+3.77)+1.1E-6*TT+1.01E-13*TT**3*EXP(7.2E-4*TT))

```

```

C      +   *((1.025/.95)*(D/(1.+(1.-D)*.5)))
C      SHEST
C      IF(IMOD.EQ.2) THEN
C      TCOR=(4.82/(351+TT)+2.434E-17*TT**4)*10.
C      ENDIF
C      SHEST
C      IF(IMOD.EQ.3) THEN
C      TCOR=
C      +(1./(0.0258*TT+3.77)+1.1E-6*TT+1.01E-13*TT**3*EXP(7.2E-4*TT))
C      +   *((1.025/.95)*(D/(1.+(1.-D)*.5)))
CC      F(D)    BUR=MWT*DAY/KG

BB=BUR/9.375D0
AB=(0.053+2.2D-4*T)/(0.053+0.016D0*BB+(2.2D0-0.005D0*BB)*T*1.D-4)

C      ABG=1.-AMIN1(0.05D0,BUR/600.D0)

      IF( (T-273.D0) .GT. 1500.D0) THEN
          B= 0.5D0
      ELSE
          B=4.4D0-1.6D0*(T-273.D0)/500 + 0.1D0*((T-273.D0)/500)**2
      ENDIF
      ABG=1.D0-0.001D0*B*BUR

      CONDT=TCOR*100
      TCOR=TCOR*AB*ABG
      ENDIF

C      PRINT *,TCOR,D,T,'    TCOR'
C      RETURN
END

FUNCTION FCP (FTTEMP,FACMOT,FOTMTL,FRDEN)
.

.

C      TABLE OF FUEL SPECIFIC HEAT VS. TEMPERATURE OF FRESH FUEL
C      WAS TAKEN FROM A.V.SALATOV ET.AL.// VNIINM 0575 04.12.89
C
      DATA FUTCPW/      270.0D0, 280.0D0, 287.0D0, 500.0D0,
#      302.0D0, 700.0D0, 310.0D0, 900.0D0, 314.0D0, 1100.0D0,
#      319.0D0, 1300.0D0, 320.0D0, 1500.0D0, 328.0D0, 1700.0D0,
#      340.0D0, 1900.0D0, 364.0D0, 2100.0D0, 390.0D0, 2300.0D0,
#      426.0D0, 2500.0D0, 470.0D0, 2700.0D0, 520.0D0, 2900.0D0,
#      594.0D0, 3100.0D0 /
      DATA NWWR, IU / 15, 1 /

C
.
.

IF(IWWER.GT.0) THEN
    FCP = POLATE (FUTCPW,T, NWWR, IU)
    ELSE
    FCP = CP(C1U,C2U,C3U,THU,EDU,T,FOTMTL)*(1.0D0- FCMP) +
#      CP(C1PU,C2PU,C3PU,THPU,EDPU,T,FOTMTL)*FCMP
    ENDIF

C
    IF (T .LT. (TM-0.1D0)) GO TO 100
    IF (IWWER.GT.0) THEN
        FCP = (1.0D0- R)*FCP + R*485.0D0
    ELSE
        FCP = (1.0D0- R)*FCP + R*FCPMOL
    ENDIF

C
    GO TO 100
C
50 CONTINUE
    IF (IWWER.GT.0) THEN
        FCP = 485.0D0
    ELSE

```

```

        FCP      = FCPMOL
        ENDIF
C
        UFCP    = 2.0D0
        PUFCP   = 5.6D0
C
100    CALL DIALOT(FTEMP,1,FDIALA,FDIALM)
        FCP=(FCP+FDIALA)*FDIALM
C
        FCP=FCPP11*FCP
        RETURN
        END

FUNCTION FTHEXP (FTEMP,FACMOT)

.
.

C
C     FOR ZR-18NB:
DIMENSION EXPDAT(34)
DATA EXPDAT/
* 0.0,    300. .
* 0.0077, 400. .
* 0.240,   600. .
* 0.451,   800. .
* 0.678,  1000. .
* 0.922,  1200. .
* 1.1820, 1400. .
* 1.4580, 1600. .
* 1.7510, 1800. .
* 2.060,   2000. .
* 2.3850, 2200. .
* 2.7270, 2400. .
* 3.0850, 2600. .
* 3.460,   2800. .
* 3.851,   3000. .
* 4.40120, 3080. .
* 4.40120, 3200. /
C
.
.
.
C
C     DATA BASE FOR UO2 : BIBI. GKAE 1983.
C
        IF(IWWR.GT.0) THEN
C
        FTHVV = POLATE(EXPDAT,T,17,1)/100.D0
        FTHEXP = FTHVV
        ENDIF
C
        FTHEXP = FTHEXP*DFEM
        RETURN
        END

FUNCTION FENTHL (TEMP      ,FCOMP      ,FOTMTL      ,FTMELT      ,FACMOT
1          ,FHFUS      )
IMPLICIT REAL*8 (A-H,O-Z)
C
C ****
C
C THIS FUNCTION IS CALLED BY SUBROUTINE ENERGY AND COMPUTES THE
C ENTHALPY OF FUEL AT A POINT RELATIVE TO ZERO DEGREES ABSOLUTE
C TEMPERATURE
C ****
C           INPUT ARGUMENTS
C ****

```

```

C      FACMOT - FRACTION OF MOLTEN FUEL
C      FCOMP - PUO2 FRACTION OF THE FUEL
C      FHEFUS - HEAT OF FUSSION OF THE FUEL (J/KG)
C      FOTMLT - FUEL OXYGEN TO METAL RATIO
C      FTMLET - FUEL MELTING TEMPERATURE (K)
C      TEMP - LOCAL TEMPERATURE (K)
C
C **** OUTPUT ****
C
C      FENTHL - LOCAL FUEL ENTHALPY RELATIVE TO ZERO DEGREES-K (J/KG)
C
C **** FCPMOL = SPECIFIC HEAT CAPACITY OF MOLTEN FUEL ( J/(KG*K) )
C
CANDR
      INCLUDE 'WWER.H'
      COMMON/INDX/K111,K1111,K11111,ITRAN
      COMMON /ANDREW/ CTHC11,CCPP11,FTHC11,FCPP11,CKMN11,CTHE11,FTHE11
      *,FP011,FQQ11,HTT11
      DIMENSION WWRENT(30)
      DATA FCPMOL / 503.D0 /
C
C      THE FOLLOWING DATA STATEMENTS CONTAIN CONSTANTS FROM MATPRO-11 FCP
C
      DATA C1U, C2U, C3U, THU, EDU / 296.7D0, 2.43D-02, 8.745D07,
      1          535.285D0, 1.577D05 /
      DATA C1PU,C2PU,C3PU,THPU,EDPU / 347.4D0, 3.95D-04, 3.860D07,
      1          571.0D0, 1.967D05 /
C
      DATA WWRENT/1.9D3, 300.0D0, 57.6D3, 500.0D0, 116.5D3, 700.0D0
      #          ,177.7D3, 900.0D0, 240.1D3, 1100.0D0, 303.4D3, 1300.0D0
      #          ,367.3D3, 1500.0D0, 432.1D3, 1700.0D0, 498.9D3, 1900.0D0
      #          ,569.3D3, 2100.0D0, 644.7D3, 2300.0D0, 726.3D3, 2500.0D0
      #          ,815.9D3, 2700.0D0, 914.9D3, 2900.0D0
      #          ,1026.3D3, 3100.0D0 /
C
C      THE FOLLOWING EQUATION IS THE INTEGRAL OF THE FUEL SPECIFIC HEAT
C      WITH RESPECT TO TEMPERATURE
C
      CPDT(C1,TH,C2,OTM,ED,T,C3) =
      #          C1*TH * ( 1.D0/ (EXP(TH/T)-1.D0))
      1          + C2 * T * T / 2.D0
      2          + C3 * OTM * EXP(-ED /(T * 8.314D0) )/2.D0
C
      TX=TEMP
      IF(TX.GT.FTMELT)TX=FTMLET
C
      FENTHL = CPDT(C1U      ,THU      ,C2U      ,FOTMLT      ,EDU
      1      ,TX      ,C3U      ) * ( 1.D0 - FCOMP )
C
      IF( FCOMP .GT. 0.D0 )FENTHL = FENTHL + CPDT(C1PU      ,THPU
      1      ,C2PU      ,FOTMLT      ,EDPU      ,TX      ,C3PU )*FCOMP
C
      IF(IWWER.GT.0) FENTHL=POLATE(WWRENT,TX,15,1)
C
      IF( TEMP .LE. FTMELT - 2.D0 ) GO TO 100
C
C
      FENTHL = FENTHL + FHEFUS * FACMOT
C
      IF(TEMP.LE.(FTMLET+2.D0))GO TO 100
C
C
      FENTHL=FENTHL+(TEMP-FTMLET)*FCPMOL
      IF(IWWER.GT.0) FENTHL=FENTHL+
      # (TEMP-FTMLET)*485.0D0
100  CONTINUE
      IF(ITRAN.NE.1) GOTO 120
C      FENTHL=FCPP11*FENTHL

```

```

120  CONTINUE
C
RETURN
END

.
.
.

SUBROUTINE FTHCON (FTEMP, FRADEN, FOTMTL, CON, DKDT, BUP)

.
.
.

C
      IWWERF=IWWER      ! VVER... CALCULATION
      IWWERF=IWWER-100   ! PWR CALCULATION
IF(IWWERF.GT.0) THEN
      IMOD=1      ! PIN-MICRO CORRELATION
      IMOD=2      ! VNIINM CORRELATION
      IMOD=3      ! KOLYADIN CORRELATION + BURNUP => PIN-MOD2

      BUPP=BUP/86400.D0
      CON=TCOR (FRADEN,FTEMP,IMOD,BUPP,COND) *100.D0
      CONBU0=CON
      CON0=COND
.
.
.

*****SHEST 28/10/96 COMMENT FOLLOWING STRINGS FOR ZERO BURNUP
      IF(BUP.LE.1.D-10) RETURN
      FFTEMP=FTEMP
      BN=BUP
C  FOR PWR FUEL USE BURNUP
      CALL BURNUP(CON,CONBU,FFTEMP,BN)
CCCCCCCCC      PRINT*,BN,CON,CONBU
      CON=CONBU

      ENDIF      ! FOR IWWER
      RETURN
C** THIS PROGRAM VALID ON FTN4 AND FTN5 **
END

.
.
.

SUBROUTINE COBILD ( T1, T2, DT,AM5, DROD, PINT, IP,IP2, Y8, Y9,
#                      Y9A,Y9B,AAO,AEO,ACO,ADO,AEO,AFO,AGO,AHO,AIO,
#                      AAI,ABI,ACI,ADI,AEI,AFI,AGI,AHI,AII, W1,  P,
#                      PERSAT , BWTFR ,AL8)

.
.
.

IF(IWWER.EQ.0) THEN
      IF(AZ8.GE.1853.0D0) GOTO 573
      570  Y6 = 2.0D0*(1.12569D-02)*EXP(-3.58908D04/(1.987D0*A28))
      572  Y7 = 2.00D0*0.761490D0*EXP(-4.81418D04/(1.987D0*A28))
      ELSEIF(IWWER.EQ.1) THEN
      Y6 = 6.45000D-02*EXP(-20242.0D0/AZ8)
      Y7 = 32.26D0*EXP(-1.35800D04/AZ8)
      ELSE
      IF(AZ8.GE.1773.0D0) GOTO 573
      Y6 = 0.51900D-02*EXP(-15355.0D0/AZ8)
      Y7 = 3.096D-03*EXP(-1.32850D04/AZ8)
C      Y6 = 55. * 0.51900D-02*EXP(-15355.0D0/AZ8)
C      Y7 = 50. * 3.096D-03*EXP(-1.32850D04/AZ8)
      ENDIF
      GOTO 574
573  CONTINUE
      IF(IWWER.EQ.0) THEN
      Y6 = 2.0D0*(1.035D-02)*EXP(-1.6014D04/AZ8)
      Y7 = 2.00D0*0.761490D0*EXP(-4.81418D04/(1.987D0*A28))
      ELSEIF(IWWER.EQ.1) THEN
      Y6 = 6.45000D-02*EXP(-20242.0D0/AZ8)
      Y7 = 32.26D0*EXP(-1.35800D04/AZ8)
      ELSE
      Y6 = 1.77200D-02*EXP(-14680.0D0/AZ8)

```

```

      Y7 = 19.610D0*EXP(-3.05388D04/AZ8)
      ENDIF
  574  CONTINUE
C
C  END WWER
.
.
.
      RETURN
END

      SUBROUTINE GAPHTC(GPTHKI, RF, PFC, TG, TF, TC, PG, GASES, FLUX,
# TFLUX,
# RUFC, RUFF, FRDEN, COLDWK, ZRO, FOTMTL, TEMPCM,
# MODFD, HGAPT,JAXIAL)

.
.
.

C SHEST COMMENT NEXT STRING
C     IF(GPTHK.LT.THKMIN)GPTHK=THKMIN
.

.
.

IF(JAXIAL.EQ.1MAX1) THEN
    H_GAP=HGAPT*5.67826334D0
    H_GAS=HGAP*SECHR*5.67826334D0
    H_SOLID=HSOLID*SECHR*5.67826334D0
    H_RAD=HGAPR*SECHR*5.67826334D0
    GAP_HE=GPTHK *0.3048D6          !/ 2.54D0
    JUMP_HE=DJMPFT *0.3048D6      !/ 2.54D0
    DROUGH_HE=DROUGH *0.3048D6   !/ 2.54D0
    HGAP_HE=GASCON_FRAP/((GPTHK+DJMPFT+DROUGH)*0.3048D0)
    C      PRINT*, H_GAP, H_GAS, H_SOLID, H_RAD
    C      PRINT*, GPSI,GTHKN
    ENDIF
***** SHEST 10-23-97 05:35PM SET HGAPT LIMIT:
    IF(HGAPT*5.67826334D0 .GE. 50000.D0) HGAPT=50000.D0/5.67826334D0
*****
    RETURN
C** THIS PROGRAM VALID ON FTN4 AND FTN5 ***
END

```

```

      SUBROUTINE STORE6 (LSECH)

.
.
.

      COMMON/BAL_SHEST/ ZTMAX,E_BURST
      CHARACTER*3 CHARBAL
      CHARACTER*30 STRO
.

.
.

***** FOR CORRECT RECORDING (TPLENUM) TO A STRIP-FILE
      TP(1)=TPLNA(1,2,1)
***** SHEST ADDITIONAL PRINTOUT FOR PRNTOT.F *****
      IF(T.EQ.0.0D0) THEN
          THGAP=1.E-3
          NT_RUPT=0
          NT_CONT=0
          J_CON =0
      ENDIF
***** CONTACT ?
      T_S=T
      IF(NSW.EQ.1 ) T_S=TCURRS/86400.D0
      IF(THGAP.LE. 0.0D0.AND. NT_CONT.EQ.0) THEN
          IF(J_CON.EQ.0) THEN
              TIME_CONT=T_S

```

```

C           TEMP_CONT=TCLADD
C           TEMP_CONT=TSREDN
C           PRINT*, TIME_CONT, TEMP_CONT, J_CON, T_S, TCLADD, TICO
C           J_CON=J_CON+1
C           ENDIF
C           IF(IGRAF.EQ.0) WRITE(0,1960) T_S,TCLADD
1960     FORMAT (/12X,'BEGINNING OF FUEL-CLADDING INTERACTION',//,
C           *          12X,'AT TIME =',F7.2,' SEC;  TCLAD =',F7.0,' K',//)
C           NT_CONT=NT_CONT+1
C           ENDIF
C           IF( NT_CONT.NE.0.AND. THGAP .GT. 1.D-3)THEN
C               IF(IGRAF.EQ.0) WRITE(0,1962) T_S,TCLADD
1962     FORMAT (/12X,'END OF FUEL-CLADDING INTERACTION',//,
C           *          12X,'AT TIME =',F7.2,' SEC;  TCLAD =',F7.0,' K',//)
C           NT_CONT=0
C           ENDIF
C
***** SHEST BURST TIME ESTIMATION *****
***** FAILURE ??? *****
C           IF(KNONUE.GT.0) THEN
C
C           IF(IFAIL.GT.0 .AND. NT_RUPT.EQ.0 .AND. IFBALN.GE.1) THEN
C               JRUPTURE=1
C               Z_BURST=ELEV(KNONUE)*0.3048D0
C               E_BURST=TCEBAL*100.D0
C               CHARBAL='YES'
C           ELSE
C               CHARBAL='NO '
C               IZ_BURST=LMAX1
C               E_BURST=EHOOP_MAX
C           ENDIF
C           PRINT*, 'FROM STORE6', EHOOP_MAX
C
C           IF(IFAIL.GT.0 .AND. NT_RUPT.EQ.0) THEN
C               JRUPTURE=1
C               TIME_FAIL=T
C               TEMP_FAIL=TCLADD
C               PG_FAIL=PGAS_1
C               IF(IFBALN.GE.1 .AND. IGRAF.EQ.0)
C               *WRITE(0,1961)T,TCLADD,DTCLADD,PGAS_1,CHARBAL,
C               *Z_BURST,E_BURST
1961     FORMAT (/12X,'CLAD FAILURE TIME  =',F7.2,' SEC',//,
C           *          12X,'CLAD FAILURE TEMP  =',F7.0,' K ',F8.3,' K/S',//,
C           *          12X,'CLAD FAILURE PGAS  =',F7.2,' MPA',//,
C           *          12X,'BALLOONING OCCURRED?      ',A3,//,
C           *          12X,' AT ELEVATION',F7.3,' (M),    MAX. STRAIN',F7.2,' (%)',//)
C
C               IF(IFBALN.EQ.0.AND.IGRAF.EQ.0 )
C               *WRITE(0,1963)T,TCLADD,DTCLADD,PGAS_1,CHARBAL,
C               *IZ_BURST,E_BURST
1963     FORMAT (/12X,'CLAD FAILURE TIME  =',F7.2,' SEC',//,
C           *          12X,'CLAD FAILURE TEMP  =',F7.0,' K ',F8.3,' K/S',//,
C           *          12X,'CLAD FAILURE PGAS  =',F7.2,' MPA',//,
C           *          12X,'BALLOONING OCCURRED?      ',A3,//,
C           *          12X,' AT AXIAL NODE',I3,'    MAX. STRAIN',F7.2,' (%)',//)
C
C               T_BURST=T
C               NT_RUPT=NT_RUPT+1
C           ENDIF
C
***** GRAFOUT *****
C
PGAS_1=PGAS
TCLADD_1=TCLADD
THGAP_1=THGAP
EHOOP_1=EHOOP_MAX
CALL GRAFOUT(UNIT,NROD,TMAX,DZ0,FMASS,VOLUME,FUELLEN,
*TCLADD,PGAS,THGAP,T_S,STR0 )
DTCLADD=ABS(TCLADD_1-TCLADD)/DT
DE_DT=ABS( EHOOP_1-EHOOP_MAX)/DT
.
.
```

```

        RETURN
        END

        SUBROUTINE PCHF( G, HFP, HGP, HIN, P, X, CL, DR, DH, HD, CHF
1 , ICWF, PFACA, SHFRV, ELEV, KAXN, ZZ, J1,
2 TSAT, RF, RG, ALPHA, CPG, TWALL, CPF, TBULK)

.
.
.
C      CONVERT SUBCOOLING TEMPERATURE FROM F TO K
C
C      DTSUBK=TFK(TSAT)-TFK(TBULK)
C      SHEST DT [F]
C      DTSUBF=(TSAT)-(TBULK)
C
C      FSUBC=1.D0+0.065D0*((RF/RG)**0.8D0)*(CPF*DTSUBK/(HGP-HFP))
C      FSUBC=1.D0+0.065D0*((RF/RG)**0.8D0)*(CPF*DTSUBF/(HGP-HFP))

.
.
.
        RETURN
        END

```

PROGRAM FRAPT6

```

        .
.
.
1941 READ(55,1941) TITLE
1941 FORMAT(A100)
C     READ(55,100,END=10000) NREST ,NCARDS ,IUNCRT ,T1,T2,ITEPLN,IWWR,
C     +IRECVR ,MPTFC2
C     READ(55,*) NREST ,NCARDS ,IUNCRT ,T1,T2,ITEPLN,IWWR,
C     +IRECVR ,MPTFC2
C     READ(55,*) ISTEPPRINT,LMAX1, IGRAF
C     READ(55,1933) TITLE,IREWET
1933 FORMAT(A10,I40)*****SHEST
        IF(IGRAF.EQ.0) THEN
        IF(ITEPLN.EQ.0)WRITE(0,'') COOLANT - WATER ',ITEPLN
        IF(ITEPLN.EQ.9)WRITE(0,'') COOLANT - FORCED HELIUM',ITEPLN
        IF(ITEPLN.EQ.10)WRITE(0,'') COOLANT - STAGNATED AIR',ITEPLN
        IF(ITEPLN.EQ.11)WRITE(0,'') COOLANT - FORCED AIR ',ITEPLN
        IF(IWWR.EQ.0) WRITE(0,'') CLADDING - ZIRCALLOY ',IWWR
        IF(IWWR.GE.1) WRITE(0,'') CLADDING - ZR+1%NB ',IWWR
        ENDIF
.
.
.
***** SHEST 13/04/95) *****
C
        OPEN(UNIT=10,FILE='GRAPH.DAT')
        OPEN(UNIT=24,FILE='MECHAN.PRO')

        NLINES=10

2001 FORMAT(A800)
        GRAPH0=' TIME ENTHALPY AVEPOW(KW) ENER_MAX1 TPLENU
*M ENT_MAX1 AVERTFUEL TERMOCOUPLE MOLTZONE PGAS ENE
*RGYINP ENERGYOUT ENTH(KJ/M) CLADINGEXT FUELEXTEX HT-MODE
* RT2 R01 R02 MWR_ENERGY FAIL_PROBAB
* RT1 SWELLING FGR H_GAP H_GAS H_SOLID
* H_RAD H_FUEL(SP) H_SPCL(SP) H_IZL(SP) H_COND(SP)
*TSPRING TCLADDI TFBOT HTC HTC_COOL HRADD
* FLUX_PL TPLENB BIO FO TETA_1
*TETA2 TAU_CONST TAU_FUEL TETA_AVE TCONSTANT *DENSIF
* DEL_RSWEL DEL_DENSIF SWTOT HEATFLUX TCLAD '
GRAPH1=' TIME TSREDN ULTIM_STR YIELD_STRS CTSTRT
* STR_BURST TGAS GAS_CON_FRAP GASCON_HE GAP_HE JUM

```

```

*P_HE      DROUGH_HE   HGAP_HE     STRESS_BAL    CHSTRS    PROBABIL'
WRITE(10,2001) GRAPH0
WRITE(24,2001) GRAPH1

***** OUTPUT FOR BALLOON2 *****
OPEN(UNIT=41,FILE='BALOON1.DAT')
OPEN(UNIT=42,FILE='BALOON2.DAT')
OPEN(UNIT=43,FILE='TABLE.OUT')

***** OUTPUT FOR PRNTOT *****
OPEN (UNIT=40,FILE='T')

***** OUTPUT FOR GRAFOUT *****
OPEN(UNIT=80,FILE='T_GRAF.DAT')

OPEN(UNIT=91,FILE='T1_RAD.DAT')
OPEN(UNIT=92,FILE='T2_RAD.DAT')
OPEN(UNIT=93,FILE='T3_RAD.DAT')
OPEN(UNIT=94,FILE='T4_RAD.DAT')
OPEN(UNIT=95,FILE='T5_RAD.DAT')
OPEN(UNIT=96,FILE='T6_RAD.DAT')

OPEN(UNIT=81,FILE='MOL1_Z.DAT')
OPEN(UNIT=82,FILE='MOL2_Z.DAT')
OPEN(UNIT=83,FILE='MOL3_Z.DAT')
OPEN(UNIT=84,FILE='MOL4_Z.DAT')
OPEN(UNIT=85,FILE='MOL5_Z.DAT')
OPEN(UNIT=86,FILE='MOL6_Z.DAT')

OPEN(UNIT=71,FILE='DEF1_Z.DAT')
OPEN(UNIT=72,FILE='DEF2_Z.DAT')
OPEN(UNIT=73,FILE='DEF3_Z.DAT')
OPEN(UNIT=74,FILE='DEF4_Z.DAT')
OPEN(UNIT=75,FILE='DEF5_Z.DAT')
OPEN(UNIT=76,FILE='DEF6_Z.DAT')

.
.

STOP
END

```

```

SUBROUTINE DEFORM(BU0,SW,DBURN) .

C SHEST 14/11/96 INTRODUCED FUEL SWELLING + DENSIFICATION
      SWELJJ=0.D0
      RSWEL=0.D0
      IG=0
      FRUDJ=0.0D0
C      PRINT *, 'DEFORM (NSW)', NSW
      DO55J=L1SKP,LFSKP,LSKP
      IG=IG+1
      IF(NSW .GE. 1 .AND. ISWEL.GT.0) THEN
C      FDENS=FRDEN*10970.D0
      RSNTR=(10680.D0-FDENS)
      TSINT=1883.D0
      FTEMP=(RWA2(J) + 459.69D0) / 1.8D0
C      BULAST=BU00(KREAL)*BUARRAY(IG)
      BULAST=(BU1-DBURN(KREAL))*BUARRAY(IG)
      IF(BULAST.LE.0.D0) BULAST=0.D0
C      BU11=BU1*BUARRAY(IG)
C      PRINT*, IG, BU11/86400, BUARRAY(IG)
      CALL FUDENS(FTEMP,BU11,FDENS,RSNTR,TSINT,COMPMT,PRVDEN,FRUD)
      IF(FRUD0(IG).LE.FRUD) THEN
          FRUD=FRUDO(IG)
      ELSE

```

```

        FRUDO(IG)=FRUD
        ENDIF
        IF(FRUD.LE.-0.4D0) FRUD=-0.4D0
        FRUDENT=FRUD*RNODLS(J)/100.D0
        FRUDJ=FRUDJ+FRUDENT

        IF (ISWEL.EQ.1) THEN
        CALL FSWELL(FDENS, COMPMT, BU11, BULAST, FTEMP, GASWL, SOLDSW)
***** SWELLING FROM FSWELL
        SWELJ= (SOLDSW+GASWL)
        SWELJJ=SWELJ+SWELJ*RNODLS(J)
        RSWEL=RSWEL+RNODLS(J)
C       IF(KREAL.EQ.LMAX1) PRINT*,BU11/86400,BU1/86400,SWELJ
        SWEL=SW(KREAL)

***** SWELLING FROM GRASS
        ELSE IF (ISWEL.EQ.2) THEN
        SWEL=BVS_Z(KREAL)/100.D0
        RSWEL=RSWEL+RNODLS(J)
C       IF(KREAL.EQ.LMAX1) PRINT*, 'FROM DEFORM', SWEL, RSWEL
C

*****
        ENDIF
        DELSW =SWEL*RNODLS(J)/3 !SWEL_GRF(IG,KREAL)*RNODLS(J)/3
C***** FRUDENT=10.0D-6/0.3048D0
        UFS(JROD,K) = DELSW ! + FRUDENT
C       PRINT*,UFS(JROD,K)
        RSW(KREAL)=DELSW
        RDEN(KREAL)=FRUDENT

C       IF(KREAL.EQ.LMAX1) WRITE(6,1961)
C       *FTEMP,
C       *BU1/86400, !RNODLS(J)*FTM,
C       *FRUD, !RNODLS(NGAP)*FTM,
C       *DELSW*FTM, FRUDENT*FTM, SOLDSW*100
1961    FORMAT(10(E11.4))
        ELSE
        UFS(JROD,K)= 0.0D0
        SWELJJ= 0.0D0
        SWEL= 0.0D0
        RSWEL= 1.0D0
        ENDIF

        RWA3(J)=RWA3(J)+ (RNODLS(J)/RNODLS(NGAP)) * UFS(JROD,K)
55 CONTINUE

        SWELJJJ=SWELJJ/RSWEL
        FRUDJJ=FRUDJ/RSWEL
CC      IF(KREAL.EQ.LMAX1) PRINT*, SWELJJJ
CC      IF(KREAL.EQ.LMAX1) PAUSE' DEFORM'
        IF (ISWEL.EQ.0) SW(KREAL)=0.0D0
        IF (ISWEL.EQ.1) SW(KREAL)=SW(KREAL) + SWELJJJ
        IF (ISWEL.EQ.2) SW(KREAL)=BVS_Z(KREAL)/100.D0
C      IF(KREAL.EQ.LMAX1) PRINT*, SW(KREAL), SW(KREAL)*3.78/3,UFS(1,KREAL)
        FUD(KREAL)=FRUDJJ
        IF(KREAL.EQ.LMAX1) DENIRR=FUD(KREAL)*100.D0
        IF(KREAL.EQ.LMAX1) SOLD=SW(KREAL)*100.D0
        IF(KREAL.EQ.LMAX1) GASWLP= GASWL*100.D0
        IF(KREAL.EQ.LMAX1) SOLDSWP= SOLDSW*100.D0
C
        .
        .
        .
***** SHEST 11/10/96 INSERT ==> (NSW.EQ.1)
        IF(MODFD.EQ.3 .AND. NSW .GE.1 )
        # THKGAP(JROD,K)=THKGPI(JROD,K)-THKGP0(1,K)
C       IF(MODFD.EQ.3 )
C       # THKGAP(JROD,K)=THKGPI(JROD,K)-THKGP0(1,K)
        .
        .
        .
***** SHEST 11/10/96 INSERT ==> (NSW.EQ.1 .AND. NSW.EQ.2)

```

```

C      IF (MODFD.EQ.3 .AND. NSW.GE.1) THKGAP(1,K)=THKGPI(1,K)-THKGP0(1,K)
C      IF (MODFD.EQ.3) THKGAP(1,K)=THKGPI(1,K)-THKGP0(1,K)
.
.
.
RETURN
END

SUBROUTINE GRAFOUT(UNIT, IROD, TMAXPLOT, DZ0,
*FMASS, VOLUME, FUELLEN, TCLADD, PGAS, THGAP, T_S, STR0)
.

.

***** * SHEST * INCLUDE 'WWER.H'
INCLUDE 'WWER.H'
INCLUDE 'WWER1.H'
COMMON/BAL_SHEST/ ZTMAX_S,TCEBAL_S
INTEGER VAR_ITER
DIMENSION PLOTTA(5000)
*,HT_MODE(50),FMASSF(1),FLEN(1)
*,TAVERAD(50),TEMP_RAD(50),RAD(50),SIGCL(50),SIEFF(50)
*,SIG02(50),EMETW_S(50),EM_W(50),EHOOP(50),SIGAX(50),TCLIN(50),
*TCLOUT(50),ZRO2W(50),TSREDN(50),ZRO(50),FENT(50),EPOIN(50)
C-GR
CHARACTER *100 VART,VARTEMPF,VARTEMPC,VARPOWER,VARBURNUP,
*VARENER,VARENTH,VARSTRES,VARSTRAI,VARDT,VARFGR,VARGAP,VARSTRF,
*VARBALL,VARPGAS,VARLEN,VARITER,VARREAL,VARREAL0,VARCRIS,VARHELP,
*VARDTFC,VARTAU,VARBIO,VARTETA
C-GR
CHARACTER*30 STR,STR1,STR0,WFAIL,PFAIL,FFAIL
.

.

.

NSHAG=NSHAG+1
IF (NSHAG.EQ.1) THEN
CALL TIME (STR0)

OPEN(UNIT=77,FILE='CLADHSS.DAT')
OPEN(UNIT=50,FILE='TMPCAV.DAT')
OPEN(UNIT=87,FILE='FENT_RAD.DAT')
OPEN(UNIT=60,FILE='BRIEF.OUT')

TEMPCS=68.D0
TK0=TFK(TEMPCS)
BINT=0.D0
TCLAD0=0.D0
TFSUR0=0.D0
TAVE0=0.D0
TTECU=0.D0
TTOPL=273.D0
TFU_COM=0.0D0
TSUR_COM=0.0D0
TAVE_COM=0.0D0
TCL_COM=0.0D0
SEFF0 = 0.0D0
SIGH0 = 0.0D0
SIGZ0 = 0.0D0
EHOOP0 = 0.0D0
MOLT_MAX=0.0D0
ZRO20=0.0D0
ZRO0=0.0D0
DTCLM=0.0D0
DECLM=0.0D0
SED=0.0D0
MCOUNT=ISTEPPRINT
IMCOUNT=0
ITCOOL=0
READ (80,*) Z0
DZ0=Z0
READ (80,*) TR1,TM1,TD1
READ (80,*) TR2,TM2,TD2
READ (80,*) TR3,TM3,TD3

```

```

        READ (80,*) TR4,TM4,TD4
        READ (80,*) TR5,TM5,TD5
        READ (80,*) TR6,TM6,TD6
        TD6=TMAXPLOT
        L=LMAX1
        ENDIF

        .
        .
        DO 200 I = K1SKP,KMXSKP,KSKP

          KZ=KZ+1
C-GRF      HEIGTH(KZ+1)=HEIGTH(KZ)+DZA(I)
C-GRF      FUELLEN=FUELLEN+DZA(I)

          TTLMW = TTLMW + EMETW(IROD,I) * DZA(I)

          SUMV = SUMV + DZA(I) * (RNODLS(LFSSKP) ** 2) * PI
*****SHEET INSERT FOLLOWING CARD INSTEAD OF PREVIOUS*****C
C      SUMV = SUMV + DZA(I) *
C      #((RNODLS(LFSSKP)**2-RP(M2SKP,I,1)**2)*PI)

          TA=0.0
          NRAD=NRAD+1
C      WRITE(0,*) DZA(I)
          EMETW_S(KZ)=EMETW(IROD,I)*DT*DZA(I)*FT
          EM_W(KZ)=EM_W(KZ)+EMETW_S(KZ)
          DL(KZ)=DZA(I)

          FRZED=0.0D0
C-GRF      NRFUEL=IGPNOD
          NZED=KZ
C-GRF

        DO 100 J = 1,IGPNOD

          LDYN = L1SKP + (J-1) * LSKP
          MDYN = M1SKP + (J-1) * MSKP

          IF (J .EQ. 1) DV = PI * ((RNODLS(LDYN+LSKP) + RNODLS(LDYN)) /
          + 2.0D0) ** 2 * DZA(I)
          IF (J .EQ. IGPNOD) DV = PI * (RNODLS(LDYN) ** 2 -
          + ((RNODLS(LDYN-LSKP) + RNODLS(LDYN)) / 2.0D0) ** 2) * DZA(I)
          IF (J .GT. 1 .AND. J .LT. IGPNOD) DV =
          + PI * (((RNODLS(LDYN) + RNODLS(LDYN + LSKP)) / 2.0D0) ** 2
          + - ((RNODLS(LDYN-LSKP) + RNODLS(LDYN))/2.0D0) ** 2) * DZA(I)

C-GRF      T_GRF(KZ,J)=TEMPP(MDYN,I,1)/1.8D0 +273.D0-17.77777D0
          POW_RAD(KZ,J)=COEFPow(KZ,J)           ! *PKWA(JRODX,I)/FT
          BURN_RAD(KZ,J)=BURN_GRF(KZ,J)
C      PRINT*, 'GRAFOU',KZ,J,BURN_RAD(KZ,J)
          BUPP=BURN_GRF(KZ,J)*86400.D0
C      PRINT*,T_GRF(KZ,J),FRDEN,FOTMTL,CON,DKDT,BUPP
          CALL FTHCON (T_GRF(KZ,J),FRDEN,FOTMTL,CON,DKDT,BUPP)
          ALAMB(KZ,J)=CON

          IF(KZ.EQ.LMAX1) THEN
            SWTOT=UFS(JRODX,I)*0.3048*1.D3
            TEMP_RAD(J)=(TEMPP(MDYN,I,1)+ 459.69D0) / 1.8D0
C            PRINT*,FOTMTL,FTMELT,FRMLTL,FHEFUS
            FENT(J)=FENTHL(TEMP_RAD(J),0.0D0,FOTMTL,FTMELT,0.0D0,FHEFUS)
&             -FENTHL(TK0,0.0D0,FOTMTL,FTMELT,0.0D0,FHEFUS)
            FENT(J)=FENT(J)/(CALLOR*THOU)
            TEMP_MAX=DMAX1(T_R, TEMP_RAD(J))
            T_R=TEMP_MAX

C            PRINT*,J,TEMP_RAD(J),LMAX1
            RAD(J)=RP(MDYN,I,1)*FT*THOU

```

```

RADFUEL(J)=RAD(J)

***** FUEL (CENTER, SURFACE) TEMPERATURE
TFUEL_M= TEMP_RAD(1)
TFUEL_S= TEMP_RAD(IGPNOD)

ENDIF

DVSUM = DVSUM + DV
TSUM = TSUM + DV * TEMPP(MDYN,I,1)
TA = TA + DV * TEMPP(MDYN,I,1)
IF (J .EQ. 1) GO TO 100

IF (QMAXHM(L1SKP) .LT. 1.0D-10) GO TO 100

R1 = RNODLS(LDYN-LSKP)
R2 = R1 + 0.5D0* (RNODLS(LDYN) - RNODLS(LDYN - LSKP))
DV1 = DZA(I) * PI * (R2 ** 2 - R1 ** 2)
R3 = RNODLS(LDYN)
DV2 = DZA(I) * PI * (R3 ** 2 - R2 ** 2)
FRZED = FRZED + (QINZ(MDYN,I,IROD) / QMAXHM(LDYN)) * DV1
+ (QINZ(MDYN+1,I,IROD) / QMAXHM(LDYN+1)) * DV2
SUM = SUM + (QINZ(MDYN,I,IROD) / QMAXHM(LDYN)) * DV1
+ (QINZ(MDYN+1,I,IROD) / QMAXHM(LDYN+1)) * DV2

100 CONTINUE

.
.
.

C     FRMOL(KZ)=FRZED/(DZA(I) * (RNODLS(LFSSKP) ** 2) * PI)
C     PRINT*,MOLT_MAX,FRMOL(KZ)
C     MOLT_MAX=DMAX1(MOLT_MAX,FRMOL(KZ))

C*** **** SHEST ACCNT CENTRAL VOID
C     TAK=TA/(DZA(I)*(RNODLS(LFSSKP)**2-RP(M2SKP,I,1)**2)*PI)

C*** **** SHEST WITHOUT ACCNT CENTRAL VOID
C     TAK=TA/(DZA(I)*(RNODLS(LFSSKP)**2)*PI)
**** ***** FARENHIET ==> KELVIN

TAVERAD(NRAD)=( TAK + 459.69D0 ) / 1.8D0

200 CONTINUE

.
.
.

T_S=T
DT_S=DT
IF (DT. GT. 1000.D0) T_S=T_S/86400.D0
IF (DT. GT. 1000.D0) DT_S=DT_S/86400.D0

PLOTDATA(1)=T_S
PLOTDATA(2)=DT_S
WRITE(66, 1000) (PLOTDATA(I),I=1,ICNT)
1000 FORMAT (' PLOTREC ',5X,1P,4E15.6,:/(5E15.6))

C SHEST 14/04/95 *****
C *** OUTER CLADD TEMPERATURE AT AXIAL NODE 'LMAX1' *****
C *** FUEL-CLADDING STRUCTURAL GAP *****
THGAP= RO1-RT2
IF (T.GE. 0.D0+DT .AND. IPHE.EQ.0) THEN
VOLSV=VOLSV0
POHE=PGAS
PRINT*, *****
PRINT*, 'WARNING: PGAS=',PGAS,' GAP=',THGAP*1.D6
PRINT*, *****
PAUSE
IPHE=1
ENDIF

```

```

        IF(NSW.EQ. 1) THEN
            TD=T/(24.D0*3600.D0)
        ELSE
            TD=T
        ENDIF

1001 FORMAT (21(E12.4))
*****N=0
DO174 K=K1SKP,KMXSKP,KSKP

    NVOIDS=0
    IF(NVOID.LT.1)GO TO 173
    IF(ELEV(K).GE.ZVOID1.AND.ELEV(K).LE.ZVOID2) NVOIDS=1
173    CONTINUE
    KDYN=K
    N=N+1
C     CALL ENERGY(TEMPP, RNODLS, FOTMTL, TEMPSCS, QINZ, QMAXHM,
* ENTH(N), TBAR, KDYN, NVOIDS)

C     IF(T.GE.TMAXPLOT-0.0001)
C     * WRITE(6,*) 'FROM GRAFOUT- N ',N,' ENTH ',ENTH(N),
C     *'TBAR',TBAR,' FOTMTL',FOTMTL,' TEMPSCS',TEMPSCS,' KDYN',KDYN

174    CONTINUE

        IF(NSHAG.EQ. 1) THEN
            IF(KREA.LT.LMAX1) THEN
                PRINT*, LMAX1,KREA
                PAUSE' STOP DUE LMAX1 > NZ'
            ENDIF
            DEN=FRDEN*10960.D0
            VDUM=(VOIDT(IROD)*FT**3)
            VDI=(FRVOID(2,IROD)+FRVOID(5,IROD))*VDUM
            VFUEL=PI*(RT2**2-RT1**2)*FUELLEN
CCCCCCC   VOLUME=VFUEL-VDI
            VOLUME=VFUEL
            FMASSF(1)=DEN*VOLUME
            FLEN(1)=FUELLEN
C             PRINT*,FRDEN,RT2,RT1

        ENDIF
        FMASS=FMASSF(1)
        FMASSA=FMASSF(1)
        FRPLOT=FRDEN
        FUELLEN=FLEN(1)
        FDLINA=FUELLEN
        CLF=FUELLEN/FMASS/CALLOR

N=0
I1=119
I2=129
I3=169
E1=0.D0
E2=0.D0
ENTAL=0.0D0
EHAVE=0.0D0
FCAL=FUELLEN/FMASS/CALLOR

DO188K=K1SKP,KMXSKP,KSKP
N=N+1
EPOIN(N)= EPSDOT(K,1,IROD)
TSREDN(N)=(TMPCAV(IROD,K) + 459.69D0) / 1.8D0
    IF(T.EQ.TIME_FAIL .AND. N.EQ.LMAX1) TSR_FAIL=TSREDN(N)
    IF(T.EQ.TIME_FAIL .AND. N.EQ.LMAX1) TIN_FAIL=TCLIN(N)
    IF(T.EQ.TIME_FAIL .AND. N.EQ.LMAX1) STRES_FAIL=SIGCL(N)
    IF (ITCOOL.EQ.0)TCOOL0=((TBULKA(IROD,K)+459.69D0)/1.8D0)-0.1D-3
    ITCOOL=ITCOOL+1
    DUM=SIGEFF(IROD,K)*PSI/1.D06

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SIEFF(N)=DUM
DUM=SIG(K,1,IROD)*PSI/1.D06
SIGCL(N)=DUM
DUM=SIG(K,2,IROD)*PSI/1.D06
SIGAX(N)=DUM
SIG02(N)=SIGY(IROD,K)*PSI/1.D06
EHOOP(N)=EPP(K,1,1)*100.D0
EHAVE=EHAVE+EHOOP(N)
DUM=PRSLCT(JROD,K)
PCOOL=PSI*DUM/1.D06
ZRO2W(N)=DMW2(IROD,K)*FT*THOU*THOU/DOZ
ZRO(N)=DMX12(IROD,K)*FT*THOU*THOU/DOZ
ZRO_MAX=DMAX1(ZRO20,ZRO(N))
ZRO_MAX=DMAX1(ZRO0,ZRO(N))
ZRO20=ZRO2_MAX
ZRO0=ZRO_MAX
TAUH=(HCOEFA(IROD,K)*HTCO)
DUMP=PKWSUM(K)
DUMH=HFXTSUM(K)
IF(U) DUMP=DUMP/FT
IF(U) DUMH=DUMH/FT
EXIT(N)=DUMH*FCAL
E2=E2+DUMH*DZA(K)*FT
HT_MODE(N)=IH(2,1,K,IROD)
ENTER(N)=DUMP*FCAL
E1=E1+DUMP*DZA(K)*FT
ENTAL=ENTH(N)*DZA(K)*FT+ENTAL
ENTH(N)=ENTH(N)/(THOU*CALLOR)
188 CONTINUE

FCAL=FUELLEN/(FMASS*CALLOR)

***** ENERGY CHARACTERISTICS FOR AXIAL SLICE OF FUEL ROD ***
TOTMWR=TOTMWREN*FCAL

E1=E1*FCAL/FUELLEN
E2=E2*FCAL/FUELLEN
E3=E1-E2
ENTALPIA=ENTAL/FUELLEN

***** DISPLAY OUTPUT *****
T_1=T*10.+1.0E-6
IT_1=AINT(T_1)
IF(NSHAG.EQ.1 .AND. IGRAF.EQ.0) THEN
  WRITE(0,*) '
  WRITE(0,*) ' THERMAL PARAMETERS FOR HOTTEST AXIAL NODE:',LMAX1
  WRITE(0,*) '
  NSHAG=NSHAG+1
ENDIF
IF(T.GE.0.0D0) THEN
  TTOPL=DMAX1(TTECU,TEMP_MAX)
C PRINT*,TTOPL,TTECU,TEMP_MAX
IF( TTECU.GE.TTOPL)THEN
  TTECU=TTOPL-100.D0
  T_R=TEMP_MAX-100.D0
  IF(TTOPL.GT.TFU_COM) TIME_FU=T
  IF(TTOPL.GT.TFU_COM) TFU_COM=TTOPL
C   PRINT*, 'MAX',TFU_COM,TTOPL,TIME_FU
  ELSE
    TTECU=TTOPL
  ENDIF
  TFSUR_MAX=DMAX1(TFSUR0,TFUEL_S)
  TFSUR0=TFSUR_MAX
IF(TFSUR0.GE.TFUEL_S ) THEN
  IF(TFSUR_MAX.GT.TSUR_COM) THEN
    TIME_SUR=T
    TSUR_COM=TFSUR_MAX
  ENDIF
  TFSUR0=TFSUR_MAX-100.D0
ENDIF
  TAVE_MAX=DMAX1(TAVE0,TAVE)
  TAVE0=TAVE_MAX
IF(TAVE0.GE.TAVE ) THEN
  IF(TAVE_MAX.GT.TAVE_COM) THEN

```

```

        TIME_AVE=T
        TAVE_COM=TAVE_MAX
        ENDIF
        TAVE0=TAVE_MAX-100.D0
    ENDIF
    TCLAD_MAX=DMAX1(TCLAD0,TCLADD)
    TCLAD0=TCLAD_MAX
    IF(TCLAD0.GE.TCLADD) THEN
        IF(TCLAD_MAX.GT.TCL_COM) THEN
            TIME_CL=T
            TCL_COM=TCLAD_MAX
            ENDIF
            TCLAD0=TCLAD_MAX-100.D0
        ENDIF
    TCLAD_MAX=DMAX1(TCLAD0,TCLADD)
    TCLAD0=TCLAD_MAX
    ENTH_MAX=DMAX1(ENTH0,ENTH(LMAX1))
    ENTH0=ENTH_MAX
    IF(IREWET.EQ.0) GOTO 1933
    IF(ENTH(LMAX1).LT.ENTH_MAX .AND. T.GT.TIME_CL .AND. NSW.EQ.2
     * .AND. ITHTC.EQ.0 .AND. ENTH(LMAX1).LE.160.D0) THEN
        TIME_HTC=T
        IF(TIME_HTC.GT.0.D0) THEN
            ITHTC=ITHTC+1
            PRINT*, ' TIME OF REWETTING', TIME_HTC
        ENDIF
    ENDIF
1933   CONTINUE
    ENS=ENTALPIA/(THOU*CALLOR)
    ENS_MAX=DMAX1(ENS0,ENS )
    ENS0 =ENS_MAX
    SEFF_MAX=DMAX1(SEFF0 ,SIEFF(LMAX1) )
    SEFF0 =SEFF_MAX
    SIGH_MAX=DMAX1(SIGH0 ,SIGCL(LMAX1) )
    SIGH0 =SIGH_MAX

    SIGZ_MAX=DMAX1(SIGZ0 ,SIGAX(LMAX1) )
    SIGZ0 =SIGZ_MAX

    EHOOP_MAX=DMAX1(EHOOP0 ,EHOOP(LMAX1) )
    EHOOP0 =EHOOP_MAX
    DTCLM =DMAX1(DTCLM,DTCLADD )

    DECLM =DMAX1(DECLM,DE_DT )

    ENDIF ! FOR T > 0
    IF(T.EQ.TIME_FAIL) ENTH_FAIL=ENTH(LMAX1)
    IF(T.EQ.TIME_FAIL) ENER_FAIL=ENTER(LMAX1)
    IF(T.EQ.TIME_FAIL) TFAV_FAIL=TAVERAD(LMAX1)

C     SED CRITERION:
C
    SED=SED + (SIEFF(LMAX1) * DABS(EDOTW) *DT)
    PRINT*, 'SED', SED,SIEFF(LMAX1), EDOTW
C
***** WRITE 2001 = DISPLAY THERAL PARAMETERS:
    IF(T.GE.1.0D-4 .AND. T.LT.1.E4 .AND. IGRAD.EQ.0)
    * WRITE(0,2001)
    * T_S,ENTER(LMAX1),
    * E1,
    * EXIT(LMAX1),
    * ENTH(LMAX1),
    * TCLADD,
    * TCLAD_MAX,
    * TSREDN(LMAX1),
    * TFUEL_S,
    * TFUEL_M,
    * FFR(1),
    * FGRTOT*100.D0
*****
CC     TIME CONSTANT
    PL=FRDEN*10960.D0
    CPFUEL= FCP (TAVE,0.0,FOTML,FRDEN)
    CALL FTHCON (TAVE,FRDEN,FOTML,CONT,DKDT,BU2)

```

```

        TAUF=(CPFUEL*PL* (RT2)**3)/(4*CONT*(2*RO2))
C      TAUF=CPFUEL*PL* (RT2**2)/(4*CONT)
        GTEMP=(TFUEL_S+TEMP_RAD(IGPNOD+1))/2
        CONG=GTHCON (GASFR, GTEMP, PGAS*1.D+6, GAPS_GRF(LMAX1)*1.D-6)
C      PRINT*,CONG,GAPS_GRF(LMAX1)*1.D-6,TAUH
        TAUG=(CPFUEL*PL*GAPS_GRF(LMAX1)*1.D-6*(RT2**2)) /(CONG*(2*RO2))
        DELCL=(RO2-RO1)
        CALL CTHCON (TSREDN, T, 0.D0, 0.D0, CCON, CDKDT)
        TAUC=CPFUEL*PL*DELCL*RT2**2/(CCON*(2*RO2))

2001 FORMAT
        *(F8.2,F7.1,' (',F5.1,')
        *F7.1,F7.1,' ',3F7.0,' (',F5.3,')',F6.1,'%')

        IF(NSW.EQ.1) THEN
          FGR_0=FGRTOT*100.D0
          SWEL_0=SWELMAX*100.D0*3
        ENDIF
          SW_MAX=DMAX1(SW0, SWELMAX*100.D0*3-SWEL_0 )
          SW0=SW_MAX
        IF(ISTEP.EQ.0) THEN
          WRITE(10,2000)
A T_S,
B ENS_MAX,
C POW, ! *FUELLEN,
D ENTER(LMAX1),
E TGAS,
F ENTH(LMAX1),
G TAVE,
H EXIT(LMAX1),
I SUM*100.D0,
J PGAS,
K E1,
L E2,
M E3,
N CLADAXEX,
O FSAXEX,
P HT_MODE(L),
Q RT2*2.0D3, ! RT2 (DIAMETER), MM
R RO1*2.0D3, ! RO1 (DIAMETER), MM
S RO2*2.0D3, ! RO2 (DIAMETER), MM
T TOTMWNR,
U FFR(1),
V RT1*2.0D3, ! RT1 (DIAMETER), MM
W SWELMAX*100.D0*3-SWEL_0, ! VOLUME FUEL SWELLING DURING TRANSIENT
X FGRTOT*100.D0-FGR_0, ! TOTAL FGR
Y H_GAP,
Z     H_GAS,
A     H_SOLID,
B     H_RAD,
C H_FUEL , ! HTC FOR SPRING
D H_ECSP+H_ECCL, ! HTC FOR SPRING
E H_IZL, ! HTC FOR SPRING
F H_COND, ! HTC FOR SPRING
G TSSTRING,
H TCLADDI,
I TFBOT,
G HTCC, ! HTC FOR AIR
K HTC_COOL, ! HTC FOR AIR
L HRADD, ! HTC FOR AIR
M FLUX_PL, ! FLUX FOR SPRING-CLAD
N (TPLENB+ 459.69D0)/1.8D0, ! T FOR BOTTOM PLENUM
O BIO,
P FO,
Q TETA1,
R TETA2,
S TAUCON,
T TAUF,
U TETA_AVER,
V TCONSTANT,
W DENIRR,
X RSW(LMAX1)*FT*1.D3, ! FUEL SWELLIING [MM]
Y RDEN(LMAX1)*FT*1.D3, ! FUEL DENSIFIC [MM]
Z SWTOT, ! FUEL SWELLIING+DENSIFICATION [MM]

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C      A TCLIN(LMAX1)
A HFL_GRF(LMAX1)*FLUX/THOU, ! HEAT FLUX [KW/M2]
B TCLADD                           ! OUTER CLAD TEMPERATURE [K]
C SED
      WRITE(77,2000) T_S,(SIGCL(N),N=1,NAXN)
      WRITE(50,2000) T_S,(TSREDN(N),N=1,NAXN)
      WRITE(87,2000) T_S,(FENT(J),J=1,IGPNOD)
      ISTEP=ISTEPPRINT
      ENDIF
      ISTEP=ISTEP-1
2000  FORMAT(1PE14.6,60(1PE14.6))
***** RADIAL TEMPERATURE DISTRIBUTION *****
      DTD=DT_S/2.0D0
** 1) MAX RADIAL FUEL TEMPERATURE

C      WRITE(50,2000) T,(TEMP_RAD(JK),JK=1,IGPNOD)
C      PRINT*, "NO",T_S, TR1+DTD , TR1-DTD
      IF(T_S.LE. TR1+DTD .AND. T_S.GE. TR1-DTD .OR.
      *T_S.LE. TR2+DTD .AND. T_S.GE. TR2-DTD .OR.
      *T_S.LE. TR3+DTD .AND. T_S.GE. TR3-DTD .OR.
      *T_S.LE. TR4+DTD .AND. T_S.GE. TR4-DTD .OR.
      *T_S.LE. TR5+DTD .AND. T_S.GE. TR5-DTD .OR.
      *T_S.LE. TR6+DTD .AND. T_S.GE. TR6-DTD )THEN
      PRINT*, "YES",T_S, TR1+DTD , TR1-DTD

C      KZ=0
      DO 3000 K=1,NMESH
          K1=K-1
          IF(K1.EQ.0) K1=1
          RKT=FLOAT(K)

          KZ=KZ+1
          IF(KZ.EQ.1.AND.T_S.LT.TR1+DTD .AND.T_S.GT. TR1-DTD )WRITE(91,2110)
          IF(KZ.EQ.1.AND.T_S.LT.TR2+DTD .AND.T_S.GT. TR2-DTD )WRITE(92,2110)
          IF(KZ.EQ.1.AND.T_S.LT.TR3+DTD .AND.T_S.GT. TR3-DTD )WRITE(93,2110)
          IF(KZ.EQ.1.AND.T_S.LT.TR4+DTD .AND.T_S.GT. TR4-DTD )WRITE(94,2110)
          IF(KZ.EQ.1.AND.T_S.LT.TR5+DTD .AND.T_S.GT. TR5-DTD )WRITE(95,2110)
          IF(KZ.EQ.1.AND.T_S.LT.TR6+DTD .AND.T_S.GT. TR6-DTD )WRITE(96,2110)

          IF(T_S.LE. TR1+DTD .AND. T_S.GE. TR1-DTD)
          *WRITE(91,2000)T_S,RAD(K),TEMP_RAD(K),COEFPow(LMAX1,K1) ,RKT,
          *COEFPow(LMAX1,K1)*BURN_Z(LMAX1),
          *COEFPow(LMAX1,K1)*PKWA(JRODX,K1)/FT,RAD(K)/RAD(IGPNOD)
          IF(T_S.LE. TR2+DTD .AND. T_S.GE. TR2-DTD)
          *WRITE(92,2000)T_S,RAD(K),TEMP_RAD(K),COEFPow(LMAX1,K1) ,RKT,
          *COEFPow(LMAX1,K1)*BURN_Z(LMAX1),
          *COEFPow(LMAX1,K1)*PKWA(JRODX,K1)/FT,RAD(K)/RAD(IGPNOD)
          IF(T_S.LE. TR3+DTD .AND. T_S.GE. TR3-DTD)
          *WRITE(93,2000)T_S,RAD(K),TEMP_RAD(K),COEFPow(LMAX1,K1) ,RKT,
          *COEFPow(LMAX1,K1)*BURN_Z(LMAX1),
          *COEFPow(LMAX1,K1)*PKWA(JRODX,K1)/FT,RAD(K)/RAD(IGPNOD)
          IF(T_S.LE. TR4+DTD .AND. T_S.GE. TR4-DTD)
          *WRITE(94,2000)T_S,RAD(K),TEMP_RAD(K),COEFPow(LMAX1,K1) ,RKT,
          *COEFPow(LMAX1,K1)*BURN_Z(LMAX1),
          *COEFPow(LMAX1,K1)*PKWA(JRODX,K1)/FT,RAD(K)/RAD(IGPNOD)
          IF(T_S.LE. TR5+DTD .AND. T_S.GE. TR5-DTD)
          *WRITE(95,2000)T_S,RAD(K),TEMP_RAD(K),COEFPow(LMAX1,K1) ,RKT,
          *COEFPow(LMAX1,K1)*BURN_Z(LMAX1),
          *COEFPow(LMAX1,K1)*PKWA(JRODX,K1)/FT,RAD(K)/RAD(IGPNOD)
          IF(T_S.LE. TR6+DTD .AND. T_S.GE. TR6-DTD)
          *WRITE(96,2000)T_S,RAD(K),TEMP_RAD(K),COEFPow(LMAX1,K1) ,RKT,
          *COEFPow(LMAX1,K1)*BURN_Z(LMAX1),
          *COEFPow(LMAX1,K1)*PKWA(JRODX,K1)/FT,RAD(K)/RAD(IGPNOD)

2110  FORMAT('TIME           RADIUS           TEMPERATURE        POWERCOEF
           *RAD_NUMBER   BURNUP_RAD  POWERRAD  REL.RADIUS')

3000  CONTINUE
      ENDIF

*****
      AXIAL PARAMETERS DISTRIBUTION *****

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*** 1) FRACTION OF MOLTEN ZONE, FUEL TEMPERATURE
    IF(T_S.LT. TM1+DTD .AND. T_S.GT. TM1-DTD .OR.
    *   T_S.LT. TM2+DTD .AND. T_S.GT. TM2-DTD .OR.
    *   T_S.LT. TM3+DTD .AND. T_S.GT. TM3-DTD .OR.
    *   T_S.LT. TM4+DTD .AND. T_S.GT. TM4-DTD .OR.
    *   T_S.LT. TM5+DTD .AND. T_S.GT. TM5-DTD .OR.
    *   T_S.LT. TM6+DTD .AND. T_S.GT. TM6-DTD) THEN
        KZ=0

        DO 3006 K=K1SKP,KMXSKP,KSXP
        MDYN1 = M1SKP + (1-1) * MSKP
        MDYN2 = M1SKP + (IGPNOD-1) * MSKP

        TZED1=(TEMPP(MDYN1,K,1)+ 459.69D0) / 1.8D0
        TZED2=(TEMPP(MDYN2,K,1)+ 459.69D0) / 1.8D0

        KZ=KZ+1
        IF(KZ.EQ.1.AND.T_S.LT.TM1+DTD .AND.T_S.GT. TM1-DTD )WRITE(81,2010)
        IF(KZ.EQ.1.AND.T_S.LT.TM2+DTD .AND.T_S.GT. TM2-DTD )WRITE(82,2010)
        IF(KZ.EQ.1.AND.T_S.LT.TM3+DTD .AND.T_S.GT. TM3-DTD )WRITE(83,2010)
        IF(KZ.EQ.1.AND.T_S.LT.TM4+DTD .AND.T_S.GT. TM4-DTD )WRITE(84,2010)
        IF(KZ.EQ.1.AND.T_S.LT.TM5+DTD .AND.T_S.GT. TM5-DTD )WRITE(85,2010)
        IF(KZ.EQ.1.AND.T_S.LT.TM6+DTD .AND.T_S.GT. TM6-DTD )WRITE(86,2010)
2010  FORMAT('TIME ELEVATION FRAC_MOLTEN TFUELMAX TFUEL_SUR
*      TCLAD_IN TCLAD_OUT ENERGY_DEP FGR SWELLING GAS
*_GENER GAS_RELEASE GAS_GEN_GR GAS_GEN_FACE GAS_GEN_EDGE BURNU
*P RAD_SWELL ENTHALPY')

        IF(T_S.LT. TM1+DTD .AND. T_S.GT. TM1-DTD )
*WRITE(81,2000)T_S,Z0+ELEV(K)*.3048D3,FRMOL(KZ)*100.D0,TZED1,TZED2,
*TCLIN(KZ),TCLOUT(KZ), ENTER(KZ)*FCAL,
*      FGR_Z(KZ),
*      EVS_Z(KZ),
*      RGJ_Z(KZ),
*      GJOUT_Z(KZ),
*      RGGL_Z(KZ),
*      RGGF_Z(KZ),
*      RGGE_Z(KZ),
*      BURN_Z(KZ),
*      RSW(KZ)*FT*1.D3,
*      ENTH(KZ),
*      ENTER(KZ)

        IF(T_S.LT. TM2+DTD .AND. T_S.GT. TM2-DTD )
*WRITE(82,2000)T_S,Z0+ELEV(K)*.3048D3,FRMOL(KZ)*100.D0,TZED1,TZED2,
*TCLIN(KZ),TCLOUT(KZ), ENTER(KZ)*FCAL,
*      FGR_Z(KZ),
*      EVS_Z(KZ),
*      RGJ_Z(KZ),
*      GJOUT_Z(KZ),
*      RGGL_Z(KZ),
*      RGGF_Z(KZ),
*      RGGE_Z(KZ),
*      BURN_Z(KZ),
*      RSW(KZ)*FT*1.D3,
*      ENTH(KZ),
*      ENTER(KZ)

        IF(T_S.LT. TM3+DTD .AND. T_S.GT. TM3-DTD )
*WRITE(83,2000)T_S,Z0+ELEV(K)*.3048D3,FRMOL(KZ)*100.D0,TZED1,TZED2,
*TCLIN(KZ),TCLOUT(KZ), ENTER(KZ)*FCAL,
*      FGR_Z(KZ),
*      EVS_Z(KZ),
*      RGJ_Z(KZ),
*      GJOUT_Z(KZ),
*      RGGL_Z(KZ),
*      RGGF_Z(KZ),
*      RGGE_Z(KZ),
*      BURN_Z(KZ),
*      RSW(KZ)*FT*1.D3,
*      ENTH(KZ),
*      ENTER(KZ)

```

```

        IF(T_S.LT. TM4+DTD .AND. T_S.GT. TM4-DTD )
*WRITE(84,2000)T_S,Z0+ELEV(K)*.3048D3,FRMOL(KZ)*100.D0,TZED1,TZED2,
*TCLIN(KZ),TCLOUT(KZ), ENTER(KZ)*FCAL,
*   FGR_Z(KZ),
*   BVS_Z(KZ),
*   RGJ_Z(KZ),
*   GJOUT_Z(KZ),
*   RGGL_Z(KZ),
*   RGGF_Z(KZ),
*   RGGE_Z(KZ),
*   BURN_Z(KZ),
*   RSW(KZ)*FT*1.D3,
*   ENTH(KZ),
*   ENTER(KZ)

        IF(T_S.LT. TM5+DTD .AND. T_S.GT. TM5-DTD )
*WRITE(85,2000)T_S,Z0+ELEV(K)*.3048D3,FRMOL(KZ)*100.D0,TZED1,TZED2,
*TCLIN(KZ),TCLOUT(KZ), ENTER(KZ)*FCAL,
*   FGR_Z(KZ),
*   BVS_Z(KZ),
*   RGJ_Z(KZ),
*   GJOUT_Z(KZ),
*   RGGL_Z(KZ),
*   RGGF_Z(KZ),
*   RGGE_Z(KZ),
*   BURN_Z(KZ),
*   RSW(KZ)*FT*1.D3,
*   ENTH(KZ),
*   ENTER(KZ)

        IF(T_S.LT. TM6+DTD .AND. T_S.GT. TM6-DTD )
*WRITE(86,2000)T_S,Z0+ELEV(K)*.3048D3,FRMOL(KZ)*100.D0,TZED1,TZED2,
*TCLIN(KZ),TCLOUT(KZ), ENTER(KZ)*FCAL,
*   FGR_Z(KZ),
*   BVS_Z(KZ),
*   RGJ_Z(KZ),
*   GJOUT_Z(KZ),
*   RGGL_Z(KZ),
*   RGGF_Z(KZ),
*   RGGE_Z(KZ),
*   BURN_Z(KZ),
*   RSW(KZ)*FT*1.D3,
*   ENTH(KZ),
*   ENTER(KZ)

```

3006 CONTINUE
ENDIF

** 2) CLADDING PERMANENT DEFORMATION

```

        IF(T_S.LT. TD1+DTD .AND. T_S.GT. TD1-DTD .OR.
*   T_S.LT. TD2+DTD .AND. T_S.GT. TD2-DTD .OR.
*   T_S.LT. TD3+DTD .AND. T_S.GT. TD3-DTD .OR.
*   T_S.LT. TD4+DTD .AND. T_S.GT. TD4-DTD .OR.
*   T_S.LT. TD5+DTD .AND. T_S.GT. TD5-DTD .OR.
*   T_S.LT. TD6+DTD .AND. T_S.GT. TD6-DTD) THEN
          KZ=0
          DO 3012 K=K1SKP,KMXSKP,KSKP
          KZ=KZ+1
          IF(KZ.EQ.1.AND.T_S.LT.TD1+DTD .AND.T_S.GT. TD1-DTD )WRITE(71,2011)
          IF(KZ.EQ.1.AND.T_S.LT.TD2+DTD .AND.T_S.GT. TD2-DTD )WRITE(72,2011)
          IF(KZ.EQ.1.AND.T_S.LT.TD3+DTD .AND.T_S.GT. TD3-DTD )WRITE(73,2011)
          IF(KZ.EQ.1.AND.T_S.LT.TD4+DTD .AND.T_S.GT. TD4-DTD )WRITE(74,2011)
          IF(KZ.EQ.1.AND.T_S.LT.TD5+DTD .AND.T_S.GT. TD5-DTD )WRITE(75,2011)
          IF(KZ.EQ.1.AND.T_S.LT.TD6+DTD .AND.T_S.GT. TD6-DTD )WRITE(76,2011)
2011  FORMAT('TIME      ELEVATION      HOOP_STRAIN      SIG_EFF      SIG_HOOP
*           SIG_AXIAL      SIG_02      M-WREACTION')
          IF(T_S.LT. TD1+DTD .AND. T_S.GT. TD1-DTD )

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```

*WRITE(71,2000)T_S,Z0+ELEV(K)*0.3048D3,EPP(K,1,1)*100.D0,
*SIEFF(KZ),SIGCL(KZ),SIGAX(KZ),SIG02(KZ),
*EMETW(IROD,K) * DZA(K)*FT
  IF(T_S.LT. TD2+DTD .AND. T_S.GT. TD2-DTD )
*WRITE(72,2000)T_S,Z0+ELEV(K)*0.3048D3,EPP(K,1,1)*100.D0,
*SIEFF(KZ),SIGCL(KZ),SIGAX(KZ),SIG02(KZ),
*EMETW(IROD,K) * DZA(K)*FT
  IF(T_S.LT. TD3+DTD .AND. T_S.GT. TD3-DTD )
*WRITE(73,2000)T_S,Z0+ELEV(K)*0.3048D3,EPP(K,1,1)*100.D0,
*SIEFF(KZ),SIGCL(KZ),SIGAX(KZ),SIG02(KZ),
*EMETW(IROD,K) * DZA(K)*FT
  IF(T_S.LT. TD4+DTD .AND. T_S.GT. TD4-DTD )
*WRITE(74,2000)T_S,Z0+ELEV(K)*0.3048D3,EPP(K,1,1)*100.D0,
*SIEFF(KZ),SIGCL(KZ),SIGAX(KZ),SIG02(KZ),
*EMETW(IROD,K) * DZA(K)*FT
  IF(T_S.LT. TD5+DTD .AND. T_S.GT. TD5-DTD )
*WRITE(75,2000)T_S,Z0+ELEV(K)*0.3048D3,EPP(K,1,1)*100.D0,
*SIEFF(KZ),SIGCL(KZ),SIGAX(KZ),SIGAX(KZ),
*EMETW(IROD,K) * DZA(K)*FT
  IF(T_S.LT. TD6+DTD .AND. T_S.GT. TD6-DTD )
*WRITE(76,2000)T_S,Z0+ELEV(K)*0.3048D3,EPP(K,1,1)*100.D0,
*SIEFF(KZ),SIGCL(KZ),SIGAX(KZ),SIGAX(KZ),
*EMETW(IROD,K) * DZA(K)*FT

3012  CONTINUE
      ENDIF

CCCCC  BURND= MAX AXIAL BURNUP :
      IF(NSW.EQ.2)  BURND= BU2 / 86400.D0
CCCCC  BURND= AVERAGE AXIAL BURNUP :
      IF(NSW.EQ.1)  BURND= BURNTOT
      .
      .
      .
      IF(NSW.EQ.1) THEN
        FGR_0=FGRTOT*100.D0
      ELSE
        FGR_END=FGRTOT*100.D0
      ENDIF
      C      PRINT *,ITRAN
      IF(T.GE.TMAXPLOT-0.0001 ) THEN
      .
      .
      .
      IF(E1.GT.0.0D0) THEN
        FKE= ENTER(LMAX1)/E1
        FK_ENTH=ENTH_MAX/ENTER(LMAX1)
      ENDIF
      SFUEL=(RT2**2-RT1**2)*1.D6
      RTM=SQT(MOLT_MAX*SFUEL+(RT1*1.D3)**2)
      IF(IFAIL.EQ.0) STRES_FAIL=0.D0
      IF(IFAIL.EQ.0) TSR_FAIL=0.D0
      .
      IF(IGRAF.EQ.0) WRITE(0,2021)
      * ENTER(LMAX1), SEFF_MAX,
      * E1,          SIGH_MAX,
      * FKE,          SIGZ_MAX,
      * ENTH_MAX,    EHOP_MAX,
      * ENS_MAX,     100.D0*TCEBAL,
      * FK_ENTH,
      * TFU_COM,     TIME_FU,
      * TCL_COM,     TIME_CL,
      * JRUPTURE,    MODFD,     TIME_FAIL,
      * ENER_FAIL,
      * ENTH_FAIL,   FGR_0,
      * TEMP_FAIL,   FGR_END,
      * TSR_FAIL,
      * TIN_FAIL,
      * TFAV_FAIL,   BURND,
      * PG_FAIL,     STRES_FAIL,
      * TEMP_CONT,   TIME_CONT,
      * DTCLM ,
      * DECLM,
      * MOLT_MAX*100.D0, RTM,
      * TOTMWR,ZR02_MAX,ZR0_MAX,ZR02_MAX+ZR0_MAX,
      * (ZR02_MAX+ZR0_MAX)*100/750.

```

```

*      Z_BURST*1000.D0
*      CALL INPTITLE(60)
*      WRITE(60,2021)
*      ENTER(LMAX1), SEFF_MAX,
*      E1,          SIGH_MAX,
*      FKE,          SIGZ_MAX,
*      ENTH_MAX,    EHOOP_MAX,
*      ENS_MAX,    100.D0*TCEBAL,
*      FK_ENTH,
*      TFU_COM,    TIME_FU,
*      TCL_COM,    TIME_CL,
*      IFAIL,      MODFD,    TIME_FAIL,
*      ENER_FAIL,
*      ENTH_FAIL,  FGR_0,
*      TEMP_FAIL,  FGR_END,
*      TSR_FAIL,
*      TIN_FAIL,
*      TFAV_FAIL,  BURND,
*      PG_FAIL,    STRES_FAIL,
*      TEMP_CONT,  TIME_CONT,
*      DTCLM ,
*      DECLIM,
*      MOLT_MAX*100.D0,RTM,
*      TOTMWR,ZRO2_MAX,ZRO_MAX,ZRO2_MAX+ZRO_MAX,
*      (ZRO2_MAX+ZRO_MAX)*100.D0/750.D0,
*      Z_BURST*1000.D0

      IF(IFAIL.NE.0) WFAIL=' YES '
      IF(IFAIL.EQ.0) THEN
      WFAIL=' NO '
      PFAIL=' NO '
      FFAIL=' NO '
      TIME_FAIL=1.D20
      ENTH_FAIL=1.D20
      TEMP_FAIL=1.D20
      PG_FAIL=1.D20
      ELSE
      IF(TCEBAL*100.D0.GT.0.0D0) EHOOP_MAX=TCEBAL*100.D0
      ENDIF
      DPRES=(PGAS-PCOOL)/((R02-R01)/((R02+R01)/2.D0))
      IF(IFAIL.NE.0.AND.STRES_FAIL.GT.DPRES+50.D0) THEN
      PFAIL=' YES '
      IF(E1.GE.260.D0 ) FFAIL=' YES '
      ELSE
      PFAIL=' NO '
      FFAIL=' NO '
      ENDIF

      EHHAVE=(EHAVE-EHOOP(LMAX1))/(NAXN)
      IF(P0HE.LE.0.0D0) PRINT*, ' WARNING P0HE!', P0HE
      IF(VOLSV.LE.0.0D0) PRINT*, ' WARNING VGP!', VOLSV
      WRITE(43,2022)

1     BURND,
2     E1,
3     ENTH_MAX,
4     TFU_COM,
5     TCL_COM,
C     6   FGR_END-FGR_0,
C     7   SW_MAX,
C     8   SIGH_MAX,
1     WFAIL,
1     WFAIL,
1     PFAIL,
1     FFAIL,
2     TIME_FAIL,
3     ENTH_FAIL,
4     TEMP_FAIL,
5     PG_FAIL,
C     1   TCEBAL*100.D0,
C     7   TIME_CONT,
C     8   TEMP_CONT,
C     1   Z_BURST*1000.D0,
1     ZRO2_MAX+ZRO_MAX,
9     EHOOP_MAX,

```

```

9  EHAVE,
2  100.D0*GRFT *22400.D0*0.143D0 /(P0HE*9.807*VOLSV*1.D-3),
2  100.D0*GRFT *22400.D0*0.857D0 /(P0HE*9.807*VOLSV*1.D-3),
2  RGT_GR*22400.D0*0.143D0 /(FMASS*THOU)
C   6  STRES_FAIL,
C   9  MOLT_MAX*100.D0,
      CALL INPTITLE(43)
2022  FORMAT(
1'    BURNUP           =',F7.1,' (MWD/KG)',/,
2'    ENERGY DEPOSITION  =',F7.0,' (CAL/G)',/,
3'    PEAK FUEL ENTHALPY =',F7.0,' (CAL/G)',/,
4'    MAX FUEL TEMPERATURE =',F7.0,' ( K )',/,
5'    MAX CLAD TEMPERATURE =',F7.0,' ( K )',/
C   6'    FGR             =',F7.1,' ( % )',/,
C   7'    FUEL VOLUME SWELLING =',F7.1,' ( % )',/,
C   8'    MAX HOOP STRESS   =',F7.0,' (MPA )',/,
1'    CLAD FAILURE      =',A7,' ,',
1'    * BALLOONING       =',A7,' ,',
1'    * PCMI             =',A7,' ,',
1'    * FRAGMENT         =',A7,' ,',
2'    FAILURE TIME       =',F7.1,' ( SEC )',/,
3'    FUEL ENTH AT FAILURE =',F7.0,' (CAL/G)',/,
4'    SUR. CL. TEMP AT FAIL=',F7.0,' ( K )',/,
5'    PRESSURE AT FAILURE =',F7.1,' (MPA )',/,
C   1'    BALLOONING STRAIN =',F7.1,' ( % )',/,
C   7'    TIME AT PCMI BEGIN =',F7.1,' ( SEC )',/,
C   8'    AVE. CL. TEMP AT PCMI=',F7.0,' ( K )',/,
C   1'    AXIAL CRACK LOCATION =',F7.0,' ( MM )',/,
1'    OXIDATION LAYER    =',F7.1,' ( MKM )',/,
9'    RESIDUAL CL. HOOP STRAIN',/,
9'    *MAX CL. HOOP STRAIN=',F7.1,' ( % )',/,
9'    *AVE CL. HOOP STRAIN=',F7.1,' ( % )',/,
4'    KR COMPOSITION     =',F7.2,' ( % VOL)',/,
4'    XE COMPOSITION     =',F7.2,' ( % VOL)',/,
4'    KR CONCENT. IN GRAINS=',F7.2,' (CM3/G)',///
C   6'    CLAD STRESS AT FAIL =',F7.1,' (MPA )',/,
C   9'    MOLTEN ZONE       =',F7.0,' ( % )',///
CALL DATE(STR)
CALL TIME(STR1)
WRITE(43,1997)  STR,STR0,STR1
WRITE(60,1997)  STR,STR0,STR1
1997  FORMAT(//,'FRAP-T6 CALCULATION',//,'DATE: ',A11,//,'TIME: ',A11,//,
          ',A11)

2021  FORMAT(//, ' ENERGY CHARACTERISTICS:                      MECHANICAL CHA
*RACTERISTICS://,
** MAX. ENERGY DEPOSITION =',F6.1,' (CAL/G)  MAX. EFF. STRESS =',
+F6.1,' (MPA)',/,
** AVE. ENERGY DEPOSITION =',F6.1,' (CAL/G)  MAX. HOOP STRESS =',
+F6.1,' (MPA)',/,
** MAX./AVERAGE.....',F6.3,'          MAX. AXIAL STRESS=',
+F6.1,' (MPA)',/,
** MAX. FUEL ENTHALPY    =',F6.1,' (CAL/G)  MAX. HOOP STRAIN =',
+F6.1,' (%)',/,
** AVE. FUEL ENTHALPY    =',F6.1,' (CAL/G)  BALLOONING STRAIN=',
+F6.1,' (%)',/,
** ENTHALPY/ENERGY.....',F6.3,/,,
** MAX. FUEL TEMPERATURE =',F6.1,' (K).....TIME= ',F6.3,' S',/,
** MAX. CLAD TEMPERATURE =',F6.1,' (K).....TIME= ',F6.3,' S',/,
** FAILURE (MODEL)      =',I2,' (',I2,').....TIME= ',F5.2,
*' S',/,
** MAX. FUEL ENERGY AT FAILURE=',F6.1,' (CAL/G)',/,
** MAX. FUEL ENTH AT FAILURE=',F6.1,' (CAL/G)  PRE-TRANSIENT FGR =',
*,F6.2,' %',/,
** SURF. CLAD TEMP. AT FAIL.=',F6.1,' (K)          TRANSIENT      FGR ='
*,F6.2,' %',/,
** AVER. CLAD TEMP. AT FAIL.=',F6.1,' (K)',/,
** INNER CLAD TEMP. AT FAIL.=',F6.1,' (K)',/,
** AVERAGE FUEL TEMP AT FAIL=',F6.1,' (K)          MAX. BURNUP      ='
*,F6.2,' (MWD/KGU)',/,
** GAS PRESSURE AT FAILURE =',F6.2,' (MPA)  HOOP STRESS AT FAIL='
*,F6.2,' (MPA)',/,
** AVE. CLAD TEMP. AT PCMI  =',F6.1,' (K) AT TIME= ',F6.3,' S',/,

```

```

** CLAD TEMPERATURE RATE      =',F6.1,' (K /S)',/,
** HOOP STRAIN RATE          =',F6.1,' (% /S)',/,
** FRACTION OF MOLTEN ZONE   =',F6.1,' (%) RADIUS = ',F6.2,' MM',/,
** TOTAL ZR-WATER REACTION   =',F6.1,' (CAL/G)',/,
** ZRO2=',F5.1,' (MKM) AZRO =',F5.1,' (MKM)',/,
** SUM OF OXIDE =',F5.1,' (MKM)', F9.2,' (%)',/,
** AXIAL CRACK LOCATION     =',F5.1,' (MM)')

GAP=THGAP
CTEMP=TCLADD
PG=PGAS
TLOC=TCEBAL_S
FMASS=FMASS*THOU
VOLUME=VOLUME*1.D6
FUELLEN=FUELLEN*THOU
WRITE(42, 1009) T,GAP,CTEMP,PG,TCEBAL_S
CLOSE(10)
1002 FORMAT('**')
1009 FORMAT(E12.4,20E12.4)
ENDIF
RETURN
END

SUBROUTINE GRASP(NPRINT,W,CI,ACAE,PRF,GSG,GOU,DIS,SV,TKO,HH,POWO,
+TK,POW,VLM,ARA,TFP,RS,TS,PRSO,TGR,RGKJ,BVSKJ,BVSJ,RETG,
+MK,MK1,IQUIT,NSW,TCURR,TMAX,DBURN)

C SHEST INSERT DIMENSIONS FOR RADIAL GAS RETENTION DISTRIBUTION
DIMENSION
* G_FACE (50,50),
* G_EDGE (50,50),
* G_GRAIN(50,50),
* BURN(50),
* BURNFR(50)
CHARACTER*400, GRAPH0,GRAPH1,GRAPH3

OPEN(UNIT=38,FILE='FGR_TOT.DAT')
OPEN(UNIT=33,FILE='FGR_TRAN.DAT')

OPEN(UNIT=39,FILE='FGR_AXI1.DAT')
OPEN(UNIT=37,FILE='FGR_AXI2.DAT')
OPEN(UNIT=36,FILE='FGR_AXI3.DAT')
OPEN(UNIT=35,FILE='FGR_AXI4.DAT')
OPEN(UNIT=34,FILE='FGR_AXI5.DAT')

OPEN(UNIT=32,FILE='FGR_RET1.DAT')
OPEN(UNIT=31,FILE='FGR_TEM1.DAT')

OPEN(UNIT=30,FILE='FGR_RADS.DAT')
OPEN(UNIT=29,FILE='FGR_RADT.DAT')
CCCCCCCCCCCCC FOR GRAIN SIZE:
C      OPEN(UNIT=200,FILE='GRAINS.DAT')
C
C
C      W(1):TS0
C      W(2):GRT
C      W(3):TGSIN
C      W(4):TGSR
C
BURNTOT=0.D0
DLZTOT=0.D0
NPRINT = 1
ITRAN = 1
IF(NSW .EQ. 1) ITRAN = 0
TSOPD=W(1)+DELT
DELT9=DELT*.9999999D0

IF(IBURN0.EQ.0) THEN

```

```

9000 FORMAT(A400)
GRAPH3=' NUMBER     REL_RADI GENERATED      TEMPERATURE    SWELLI
*NG   FGR_RADI  GAS_FACE   GAS_EDGE   GAS_GRAIN   GAS_RET
*RADIUS RAD_RETEN  POROSITY
GRAPH1=' TIME      FGR_TRA RETAINED    GAS_RELEASE  GAS_RE
*TAIN GAS_GENER ERROR   I_RETAIN  CE_RETAIN  I_RELEASE  CE_
*RELEASE TCENTER  TSURFACE
GRAPH0=' TIME      J        SWELL(J)  GAS_RETAIN  GAS_RE
*LESE GAS_GRAIN GAS_FACE   GAS_EDGE   FGR(J)    SUM_RETAIN TRE
*GIONLINE TCENTER  TSURFACE  POWER     BURNUP'
WRITE(39,9000) GRAPH0
WRITE(37,9000) GRAPH0
WRITE(36,9000) GRAPH0
WRITE(35,9000) GRAPH0
WRITE(34,9000) GRAPH0
WRITE(33,9000) GRAPH1
WRITE(38,9000) GRAPH1
WRITE(29,9000) GRAPH3
WRITE(30,9000) GRAPH3

IBURN0=IBURN0+1
ENDIF
***** SHEST 27/04/96
URAN=238.0D0/(238.0D0+32.0D0)
URAN=0.882
IF(ITRAN.EQ.0)   TSHEST=TS0PD
IF(ITRAN.NE.0)   TS0_S=TS0PD-TSHEST
.
.
***** SHEST 27/04/96 *****
SUMRET=RGGF+RGGE+RGGL
BVS$=BVS*100.D0
KEND=AINT(KF1)
TDAY=TS0PD/(3600.D0*24.D0)
TMAX_0=TMAX- 5.D0*(3600.D0*24.D0)
DLZ=DL(J)*0.3048D0
FMAS=FMASSA*DLZ/FDLINA
POWER=POW(J)/0.3048D0
DTDAY=TDAY-TDAY0
BURN(J)=BURN(J)+POWER*DTDAY*DLZ/(URAN*FMAS*1000.D0)
BURNFR(J)=BURNFR(J)+DBURN(J)/86.4D3
BURNTOT=BURNTOT+BURNFR(J)*DLZ
DLZTOT=DLZTOT+DLZ
BURN_Z(J)=BURN(J)
C      PRINT *, 'FROM GRASF ',URAN,POWER,DTDAY,DLZ,FMAS
C
C      PRINT*, '!!!!!! GRASF TS',J,BURNTOT,TS
C      PAUSE 'GRASF !!!!'
IF(ITRAN.EQ.0 .AND. J.EQ. LMAX1 .AND. IGRAF.EQ.0)
*WRITE(0,2001) TS0PD/(3600.D0*24.D0),TS(KF+1,J),TS(1,J),FGRT*100.D0
*,POWER,BURN(J),BURNFR(J)
C      IF(ITRAN.EQ.0 .AND. J.EQ. LMAX1 .AND. IGRAF.EQ.0)
C      *WRITE(0,2011) T,TS(KF+1,J),TS(1,J),FGRT*100.D0
*,POWER,BURN(J),BURNFR(J)
IF(ITRAN.EQ.0 ) THEN
IF(ISTEP. EQ.0) THEN
IF(J.EQ.LMAX1)
*WRITE(39,2009) TDAY,J,BVSJ(J),RGJ,GJOUT,RGGF,RGGE,
*FGRJ/AVN,
*SUMRET,TK(1,J)/1.D0,TS(1,J),TS(KF,J),POW(J)/0.3048D0,BURN(J)

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      IF(J.EQ.2)WRITE(37,2009)TDAY,J,BVSJ(J),RGJ,GJOUT,RGGL,RGGF,RGGE,
      *FGRJ/AVN,
      *SUMRET,TK(1,J)/1.D0,TS(1,J),TS(KF,J),POW(J)/0.3048D0,BURN(J)

      IF(J.EQ.3)WRITE(36,2009)TDAY,J,BVSJ(J),RGJ,GJOUT,RGGL,RGGF,RGGE,
      *FGRJ/AVN,
      *SUMRET,TK(1,J)/1.D0,TS(1,J),TS(KF,J),POW(J)/0.3048D0,BURN(J)

      IF(J.EQ.4)WRITE(35,2009)TDAY,J,BVSJ(J),RGJ,GJOUT,RGGL,RGGF,RGGE,
      *FGRJ/AVN,
      *SUMRET,TK(1,J)/1.D0,TS(1,J),TS(KF,J),POW(J)/0.3048D0,BURN(J)
      IF(J.EQ.5)WRITE(34,2009)TDAY,J,BVSJ(J),RGJ,GJOUT,RGGL,RGGF,RGGE,
      *FGRJ/AVN,
      *SUMRET,TK(1,J)/1.D0,TS(1,J),TS(KF,J),POW(J)/0.3048D0,BURN(J)

      ENDIF
      ENDIF

***** FOR AXIAL DISTRIBUTION

      FGR_Z(J)=FGRJ*100.D0/AVN
      BVS_Z(J)=BVSJ(J)*100.D0
      RGJ_Z(J)=RGJ
      GJOUT_Z(J)=GJOUT
      RGGL_Z(J)=RGGL
      RGGF_Z(J)=RGGF
      RGGE_Z(J)=RGGE
*****
      IF(J.EQ.1MAX1.AND.TCURR.GE.TMAX_0 .AND. ISTEAD.EQ.0) THEN
      IF(IGRAF.EQ.0) WRITE(0,1961)TDAY,TS(1,J),TS(KF,J)
1961  FORMAT(5X,'TIME:',F7.0,', TEMPERATURE:',2F8.0)
C      PAUSE
      ISTEAD=ISTEAD+1
      GPELL=((GSG(KF,J)/AVN)/ARA(KF,J))
      PRINT*,GPELL,GSG(KF,J)/AVN,ARA(KF,J)

      VOLSL=0.D0
      RMASS=0.0D0
      DO K=2,KF
      VOLSL=VOLSL+ VLM(K,J)
      ENDDO
      C      PRINT*, 'MASSA SLICE [KG]',FMASS
      ROFUEL=FMAS*1000/VOLSL           ! [G/CM3]

      DO K=2,KF
      UNLESS=AVN/GSG(K,J)
      OTN_RAD=RS(K,J)/RS(KF,J)
      RMASS=VLM(K,J)*ROFUEL           ! [MASS IN G]
      C      PRINT*,     RMASS, ROFUEL,VLM(K,J),VOLSL

      WRITE(30,2010)
A K,
B OTN_RAD,
C RGKJ(K,J)*UNLESS,
D TS(K,J),
E BVSJ(K,J),
F GOU(K,J)*UNLESS/AVN,
J G_FACE (K,J)*UNLESS,
H G_EDGE (K,J)*UNLESS,
I G_GRAIN(K,J)*UNLESS,
G ((GSG(K,J)/AVN)/ARA(K,J))/GPELL,
K RS(K,J)*10.D0,                                ! [CM]
L (G_FACE (K,J)+G_EDGE(K,J)+G_GRAIN(K,J))*22.4D3/RMASS,! [CM3/G]
M PRF_GRF(K,J)                                  ! POROSITY
      ENDDO

      ELSE
      IF(J.EQ.1MAX1) THEN
      IF(ISTEP. EQ.0) THEN
      WRITE(32,2009)
A TSO_S.
B J,

```

```

C BVSJ(J),
D RGJ,
E GJOUT,
F RGGL,
G RGGF,
H RGGE,
I FGRJ/AVN,
J SUMRET,
K TS(1,J)/1.0D0,
L TS(KF,J)/1.0D0,
M TS(2,J)/1.0D0

SWELMAX=BVSJ(J)/3.0D0

ENDIF
ENDIF
ENDIF

C
IF(J.EQ.IMAX1.AND.TCURR.GE. TMAX-1.0E-6 ) THEN
  VOLSL=0.D0
  DO K=2,KF
    VOLSL=VOLSL+ VLM(K,J)
    PRINT*,      ROFUEL,FMAS,VOLSL
  ENDDO
  ROFUEL=FMAS*1000.D0/VOLSL

  DO K=2,KF
    OTN_RAD=RS(K,J)/RS(KF,J)
    RMASS=VLM(K,J)*ROFUEL           ! [MASS IN G]
    UNLESS=AVN/GSG(K,J)
    WRITE(29,2010)
    A   K,
    B OTN_RAD,
    C RGKJ(K,J)*UNLESS,
    D TS(K,J),
    E BVSKJ(K,J),
    F GOU(K,J)*UNLESS/AVN,
    G G_FACE (K,J)*UNLESS,
    H G_EDGE (K,J)*UNLESS,
    I G_GRAIN(K,J)*UNLESS,
    J ((GSG(K,J)/AVN)/ARA(K,J))/GPELL,
    K RS(K,J)*10.D0,                  ! [CM]
    L (G_FACE (K,J)+G_EDGE (K,J)+G_GRAIN(K,J))*22400.D0/RMASS, ! [CM3]
    M PRF_GRF(K,J)                   ! POROSITY
    ENDDO
    ENDIF

.
.

.
.

TDAY0=TDAY
C PRINT FUEL ROD TOTAL CHARACTERISTICS
C FOR STEADY-STATE AND TRANSIENT CONDITIONS:
  IF(ITRN.EQ.0) THEN
  IF(ISTEP. EQ.0) THEN
    WRITE(38,2010)
    A TS0PD/(3600.D0*24.D0),
    B FGRT,
    C RGT*22400.D0,
    D GTOUT*22400.D0,
    E GRFT*22400.D0,
    F GGT*22400.D0,
    G ERR*100.D0,
    H RETI*22400.D0,
    I RETC*22400.D0,
    J OUTI*22400.D0,
    K OUTC*22400.D0,
    L TS(1,IMAX1)/1.D0,
    M TS(KF,IMAX1)/1.D0
    FGRTOT=FGRT

  ISTEP=ISTEPPRINT
  ENDIF
  ENDIF

```

```

        IF(ITRAN.NE.0 .OR. TCURR.EQ.0.0D0) THEN
        IF(ISTEP. EQ.0) THEN
          WRITE(33,2010)
        *TS0_S ,FGRT,      RGT*22400.D0,
        *                  GTOUT*22400.D0,
        *                  GRFT*22400.D0,
        *                  GGT*22400.D0,
        *                  ERR*100.D0,RETI*22400.D0,RETC*22400.D0,
        *OUTI*22400.D0,OUTC*22400.D0,TS(1,LMAX1)/1.0D0,TS(KF,LMAX1)/1.0D0
          FGRTOT=FGRT

          ISTEP=ISTEPPRINT
        ENDIF
        ENDIF
745 CONTINUE

.
.
.
RETURN
END

```

```

FUNCTION GCONR2(GMIX, GTEMP, GPRES, GPTHK)

.
.
.
C     SHEST 5/28/98 5:30AM
C     IF(GPTHK.LE.4.4D-6) GPTHK=4.4D-6
.
.
.
RETURN
END

```

```

SUBROUTINE FSWELL (FDENS, COMP, BU, BUL, FTEMP, GASWL, SOLDSW)
IMPLICIT REAL*8 (A-H,O-Z)
C
C     COMP    = INPUT PLUTONIA CONTENT (WEIGHT PERCENT)
C     FDENS   = INPUT INITIAL DENSITY OF THE FUEL (KG/M**3)
C     FTEMP   = INPUT TEMPERATURE OF THE FUEL RING (K)
C     BU      = INPUT BURNUP TO END OF TIME STEP (MW-S/KG-U)
C     BUL     = INPUT BURNUP TO END OF LAST TIME STEP (MW-S/KG-U)
C
C     GASWL  = OUTPUT FUEL SWELLING DUE TO GAS FISSION PRODUCTS
C               (FRACTION)
C     SOLDSW = OUTPUT FUEL SWELLING DUE TO SOLID FISSION PRODUCTS
C               (FRACTION)
C
C     FS WELL WAS DEVELOPED AND PROGRAMMED BY R. E. MASON - JUNE 1978.
C
C     THE UO2 SWELLING CORRELATION IS BASED ON THE FOLLOWING DATA
C           CHUBB, ET AL., NUCLEAR TECHNOLOGY 18 (1973)
C           TURNBULL, JOURN. NUCL. MATER., 50 (1974)
C           BANKS, JOURN. NUCL. MATER., 54 (1974)
C           DANIEL ET AL., WAPD - 263 (1962)
C
C           - PROGRAM -
C
C     BUS    = FDENS * 2.974D+10 * (BU - BUL)
C     SOLDSW = BUS * 2.5D-23
C     IF (FTEMP .LT. 2800.D0) GO TO 25
C     GASWL = 0.0D0
C     GO TO 50
25  CONTINUE
      GASWL=(8.80D-50*((2800.D0-FTEMP)**11.73D0)*EXP(-2.4D-10*BU*FDENS)
      #                   *EXP(-0.0162D0*(2800.D0-FTEMP))) * BUS
50  CONTINUE
      CALL DIALOT(FTEMP,9,FDIALA,FDIALM)
      GASWL=(GASWL+FDIALA)*FDIALM
      SOLDSW=(SOLDSW+FDIALA)*FDIALM

```

```

      RETURN
C** THIS PROGRAM VALID ON FTN4 AND FTN5 **
      END

      SUBROUTINE FUDENS (FTEMP, BU, FDENS, RSNTR, TSINT, COMP, PRVDEN,
* FUDENT)
      IMPLICIT REAL*8 (A-H,O-Z)
C
C      FUDENS CALCULATES IRRADIATION-INDUCED DENSIFICATION.
C
C      FUDENS = OUTPUT FUEL DIMENSIONAL CHANGE (%)
C
C      FTEMP   = INPUT FUEL TEMPERATURE (K)
C      BU      = INPUT BURNUP (MW-S/KG-U)
C      FDENS   = INPUT FUEL DENSITY (KG/M**3)
C      RSNTR   = INPUT MAXIMUM DENSITY CHANGE DETERMINED BY A RESINTERING
C                  TEST OF 1973 K FOR 24 HOURS (KG/M**3)
C      TSINT   = INPUT FUEL SINTERING TEMPERATURE (K)
C      COMP    = INPUT PLUTONIA CONTENT (WEIGHT PERCENT)
C      PRVDEN = INPUT TOTAL DENSIFICATION FROM PREVIOUS TIME STEP (%)
C
C      FUDENS WAS DEVELOPED AND PROGRAMMED BY C. S. OLSEN (JANUARY 1975).
C      UPDATED AND CORRECTED BY B. W. BURNHAM (OCTOBER 1975).
C      FUDENS WAS MODIFIED BY R. E. MASON (NOVEMBER 1978).
C
C      DIMENSION C(2),B(5)
C      DATA C / 10.97D0, 11.46D0/
C      DATA B / 3.0D0, 1.00D0, 3.0D0, 2.00D0, 35.00D0/
C      DLEN2(ALEN,BU,ABU) = -B(1) + ALEN + B(2)* EXP(-B(3)*(BU + ABU))
C      #           + B(4) * EXP(-B(5) * (BU + ABU))
C      DLEN3(BU) = -B(2)*B(3)* EXP(-B(3)*BU) - B(4)*B(5)* EXP(-B(5)*BU)
C      FBU = BU * 1.0202D-05
C      TS = TSINT - 2.7315D02
C
C      IF RSNTR OR TSINT IS NOT DEFINED BY USER, THE DEFAULT VALUE IS
C
C      TSINT = 1873 K.
C
C      IF (TSINT .LE. 0.0D0) TS = 1600.0D0
C      ROTH = C(1)*C(2)/(0.01D0*COMP*C(1) + (1.0D0- 0.01D0*COMP)*C(2))
C      DE = FDENS/(ROTH*10.0D0)
C
***** <SHEST> IF FUEL DENSITY IS .LT. RSINT :
C      IF ((FTEMP .GE. 1000.D0) .AND. (RSNTR .GT. 0.D0)) DLEN1 = 0.00285D0*
#RSNTR
C      IF ((FTEMP .LT. 1000.D0) .AND. (RSNTR .GT. 0.D0)) DLEN1 = 0.00150D0*
#RSNTR
C
***** <SHEST> IF FUEL DENSITY IS .GE. RSINT :
C      IF ((FTEMP .GE. 1000.D0) .AND. (RSNTR .LE. 0.D0))
#      DLEN1 = 66.6D0*(100.0D0- DE)/(TS - 1180.0D0)
C      IF ((FTEMP .LT. 1000.D0) .AND. (RSNTR .LE. 0.D0))
#      DLEN1 = 22.2D0*(100.0D0- DE)/(TS - 1180.0D0)
C
      X3 = 0.0D0
      X4 = 1.0D0
      AL1 = DLEN1
      AL3 = 3.0D0- AL1
      AL4 = 0.0D0
      IF (AL3 .LE. 4.27D-03) GO TO 30
      DO 15 I = 1,6
      Y2 = DLEN2(AL3,X4,AL4)
      Y1 = DLEN2(AL3,X3,AL4)
      IF (Y1*Y2 .LE. 0.D0) GO TO 20
      X3 = X4
      X4 = X4 + 1.0D0
      IF (I .EQ. 6) GO TO 45
15  CONTINUE
20  CONTINUE
      X1 = X3
      DO 25 J = 1,50
      X = X1 - DLEN2(AL3, X1, AL4) / DLEN3(X1)
      ERR = ABS((X - X1) * 100.0D0/X)
      IF (ERR .LE. 2.0D-04) GO TO 35
      X1 = X
25  CONTINUE
30  AL3 = 2.996D0
      AL2 = 5.384D0
      GO TO 40
35  AL2 = X
40  CONTINUE
      FUDEN = DLEN2(AL3, FBU, AL2)

```

```

        IF (BU .LT. 1728)    FUDEN = 0.0D0
        GO TO 50
C
        45 PRINT 100
100 FORMAT (1X,/45H NO ROOTS FOUND BETWEEN 0 AND 6000 MWS/MT U02)
        FUDEN = 0.0D0
      50 CONTINUE
        FUDENT=FUDEN
        IF (ABS(FUDEN) .LE. ABS(PRVDEN))  FUDENSS = 0.0D0
        IF (ABS(FUDEN) .GT. ABS(PRVDEN))  FUDENSS = FUDEN - PRVDEN
C
        CALL DIALOT(FTEMP,11,FDIALA,FDIALM)
        FUDENSS=(FUDENSS+FDIALA)*FDIALM
        RETURN
C** THIS PROGRAM VALID ON FTN4 AND FTN5 **
END

```

```

SUBROUTINE MELT (TCLAD,UMELET,CTMELT,PFR1)
C
C      IMPLICIT REAL*8 (A-H,O-Z)
C
C      COMMON BLOCK/MATPRC/STORES MATPRO PARAMETERS USED TO DETERMINE
C      CLADDING MATERIAL PROPERTIES
C
C      REVISE /MATPRC/ COMMON BLOCK

***** SHEST COMMENT FOLLOWING STRING 26/12/96
C      INCLUDE 'MATPRC.H'

C      DTMPCL = MAXIMUM CIRCUMFERENTIAL VARIATION IN CLADDING TEMPERA-
C      TURE (K)
C      CANRIN = CONTRACTILE STRAIN RATIO DURING UNIAXIAL TENSILE TEST.
C                  CIRCUMFERENTIAL STRAIN/RADIAL STRAIN
C      KAXMTP = AXIAL NODE NUMBER
***** SHEST COMMENT FOLLOWING STRING 26/12/96
C      INCLUDE 'PHYPRO.H'
C      SUBROUTINE MELT DETERMINES IF A ROD HAS FAILED BY MELTING
C                  -- INPUT ARGUMENTS --
C      TCLAD      TEMPERATURE OF CLADDING ( DEG K )
C      UMELET     USER-SELECTED MELT TEMPERATURE ( DEG K )

C                  -- OUTPUT ARGUMENTS --
C
C      PFR1      FAILURE INDICATOR (=1 IF CLADDING MELTED)
C
***** SHEST COMMENT FOLLOWING STRING 26/12/96
C      DATA DUM/ 0.D0/
C

***** SHEST COMMENT FOLLOWING STRING 26/12/96
C      IF ( UMELET .NE. 0.D0) GO TO 5
C      UMELET = CTMELT
      5 IF ( UMELET .GE. TCLAD ) GO TO 10
          PFR1 = 1.0D0
          GO TO 20
      10 PFR1 = 0.0D0
      20 CONTINUE
C
C      PRINT*, 'FORM MELT = UMELET,TCLAD,PFR1', UMELET,TCLAD,CTMELT,PFR1
      RETURN
C** THIS PROGRAM VALID ON FTN4 AND FTN5 **
END

```

```

SUBROUTINE BALON2 (GMIX   ,FTEMP   ,STRNL  ,STRNR  ,STRNA  ,STRNC
#      ,RAD    ,TWALL  ,CTEMP   ,DELZ   ,FCP    ,FRP    ,FAP
#      ,ACD    ,AAD    ,ARD    ,FNCK   ,FNCN   ,CWKF   ,CWNF
#      ,STEMP  ,HTCS   ,TSTM   ,RTEMP  ,ACS    ,AAS    ,ARS
#      ,ACE    ,AAE    ,ARE    ,DBYTH  ,DBYZ   ,STRESF ,TSTRES

```

```

#           ,DISP    ,DEH     ,DEA      ,RSTRAN ,RAVE    ,STRESR ,STRESA
#           ,RADC    ,RADR    ,DZ0      ,CLDBRN )
C
.
.
C ***** LU      YES/NO BENDING
C      DISP(K,J) = 0.D0
.
.
C ***** LU LIMIT
C      IF(GPTHK.LT.1.5D-05) GPTHK=1.5D-05
C *****
.
.
RETURN
END

SUBROUTINE PRNTOT(T_BURST,TIM_MAX,DZ0,FMASS,VOLUME,FUELLEN,T_S,
*STR0)
.
.
N = 0
DO1288K=KAX,KMAX,KSKP
N = N+1
DUM=RSW(N)
IF (.NOT.U) DUM = DUM * DOZ
IF (U) DUM = DUM * FTMM
1288 ADUM(N) = DUM
WRITE (6,1290) DIM(IU,2), (ADUM(K),K=1,N)
1290 FORMAT( 36H DISPLACEMENT DUE TO SWELLING          ,A6,1PE13.3,5E14.3)
.
.
IF(T.GE.TIM_MAX-0.00001D0)      THEN
C      IF (IGRAF.NE.0) PAUSE'          PAUSE FOR HISTORY FROM PRNTOT.FOR'
CALL DATE(STR)
CALL TIME(STR1)

WRITE(40,1996) EBURST
WRITE(40,1996) STRAIN_B*100
WRITE(40,1996) T_BURST

***** FREE GAS VOLUME *****
WRITE(40,135)DIM(IU,2),V(10)
WRITE(40,501)V(1)*100
WRITE(40,502)V(2)*100
WRITE(40,503)V(3)*100
WRITE(40,504)V(4)*100
WRITE(40,505)V(5)*100
WRITE(40,506)V(6)*100
WRITE(40,507)V(7)*100
WRITE(40,508)V(8)*100
WRITE(40,509)V(9)*100
WRITE(40, 1002) FMASS,FMASS/VOLUME,FUELLEN

WRITE(40 ,1997) STR,STR0,STR1

WRITE( 6 ,1997) STR,STR0,STR1
1997 FORMAT(//,'FRAP-T6 CALCULATION',//,'DATE: ',A11,//,'TIME: ',A11,//,
*'          ',A11)

1002 FORMAT(//,'MASS=',F9.4,/,,'DENSITY=',F6.2,/,,'FUEL LENGTH=',F9.4)
ENDIF

1995 FORMAT(A20)

```

```

1998 FORMAT(10X,A20)
1996 FORMAT(10E12.4)
RETURN
END

PROGRAM GRAFDATA
CHARACTER*11 STEP
CHARACTER*18 ISTEP, BLANK
REAL IOXTN,LOCRODPW,METWRE,MIDTEMPP
DATA STEP //' PLOTREC'/
ISTEP=' '
DIMENSION DATAINT(13),
*CLADAXSS(50),CLADHSN(50),CLADHSS(50),CLADITE(50),CLADOTE(50),
*CLADPASN(50),CLADPHSN(50),CLADPRSN(50),CLADRSN(50),CLADSNI(50),
*CLADSSI(50),CLADYSS(50),COLBLKTE(50),COLMSFLX(50),COLPE(50),
*COLGL(50),CRTHTFLEX(50),CTEMP(50),EFCLADSS(50),ELEV(50),
*FSDSP(50),FSTEMP(50),GAPHTC(50),GAPPR(50),HEATTRMD(50),
*IOXTN(50),LOCRODPW(50),METWRE(50),OOXTN(50),OXSTN(50),
*STRUPIP(50),STRUCRG(50),SURHTC(50),SURHTFLX(50),THMGAPIP(50),
*THMRG(50),RPMFS(50),RPMCI(50),RPMMX(50),MIDTEMPP(50),FAILFLAG(50),
*DATA1(250),FDISO(50)
NAMELIST/INP/AKSNUMBER,ISTEPPRINT
OPEN(1,FILE='STRIPP')
OPEN(51,FILE='T')
READ(51,*) TEND,DZ0,LMAX,NAXN,ISTEPPRINT

1961 FORMAT(F10.1,E12.4,3I5)

IF(ISTEPPRINT.LT.1)
*PRINT*, ' !!! STEP FOR PRINT IS TOO LOW =',ISTEPPRINT

NM=NAXN
NM1=NM*5

OPEN(2,FILE='INTDATA.DAT',STATUS='NEW')
OPEN(3,FILE='CLADAXSS.DAT',STATUS='NEW')
OPEN(4,FILE='CLADHSN.DAT',STATUS='NEW')
OPEN(5,FILE='CLADHSS.DAT',STATUS='NEW')
OPEN(6,FILE='CLADITE.DAT',STATUS='NEW')
OPEN(7,FILE='CLADOTE.DAT',STATUS='NEW')
OPEN(8,FILE='CLADPASN.DAT',STATUS='NEW')
OPEN(9,FILE='CLADPHSN.DAT',STATUS='NEW')
OPEN(10,FILE='CLADPRSN.DAT',STATUS='NEW')
OPEN(11,FILE='CLADRSN.DAT',STATUS='NEW')
OPEN(12,FILE='CLADSNI.DAT',STATUS='NEW')
OPEN(13,FILE='CLADSSI.DAT',STATUS='NEW')
OPEN(14,FILE='CLADYSS.DAT',STATUS='NEW')
OPEN(15,FILE='COLBLKTE.DAT',STATUS='NEW')
OPEN(16,FILE='COLMSFLX.DAT',STATUS='NEW')
OPEN(17,FILE='COLPE.DAT',STATUS='NEW')
OPEN(18,FILE='COLQL.DAT',STATUS='NEW')
OPEN(19,FILE='CRTHTFLEX.DAT',STATUS='NEW')
OPEN(20,FILE='CTEMP.DAT',STATUS='NEW')
OPEN(21,FILE='EFCLADSS.DAT',STATUS='NEW')
OPEN(22,FILE='ELEV.DAT',STATUS='NEW')
OPEN(23,FILE='FSDSP.DAT',STATUS='NEW')
OPEN(24,FILE='FSTEMP.DAT',STATUS='NEW')
OPEN(25,FILE='GAPHTC.DAT',STATUS='NEW')
OPEN(26,FILE='GAPPR.DAT',STATUS='NEW')
OPEN(27,FILE='HEATTRMD.DAT',STATUS='NEW')
OPEN(28,FILE='IOXTN.DAT',STATUS='NEW')
OPEN(29,FILE='LOCRODPW.DAT',STATUS='NEW')
OPEN(30,FILE='METWRE.DAT',STATUS='NEW')
OPEN(31,FILE='OOXTN.DAT',STATUS='NEW')
OPEN(32,FILE='OXSTN.DAT',STATUS='NEW')
OPEN(33,FILE='STRUPIP.DAT',STATUS='NEW')
OPEN(34,FILE='STRUCRG.DAT',STATUS='NEW')
OPEN(35,FILE='SURHTC.DAT',STATUS='NEW')
OPEN(36,FILE='SURHTFLX.DAT',STATUS='NEW')
OPEN(37,FILE='THMGAPIP.DAT',STATUS='NEW')
OPEN(38,FILE='THMRG.DAT',STATUS='NEW')

```

```

OPEN(39,FILE='RPMFS.DAT',STATUS='NEW')
OPEN(40,FILE='RPMCI.DAT',STATUS='NEW')
OPEN(41,FILE='RPMMX.DAT',STATUS='NEW')
OPEN(42,FILE='MIDTEMPP.DAT',STATUS='NEW')
OPEN(43,FILE='FAILFLAG.DAT',STATUS='NEW')
2 CONTINUE
READ(1,1,ERR=3) ISTEP
IF(ISTEP(1:9).EQ.STEP) THEN
BACKSPACE 1
READ(1,*) BLANK,
*DATAINT,
*(CLADAXSS(L),L=1,NM),(CLADHSN(L),L=1,NM),(CLADHSS(L),L=1,NM),
*(CLADITE(L),L=1,NM),(CLADOTE(L),L=1,NM),
*(CLADPASN(L),L=1,NM),(CLADPHSN(L),L=1,NM),(CLADPRSN(L),L=1,NM),
*(CLADRSN(L),L=1,NM),(CLADSNI(L),L=1,NM),
*(CLADSSI(L),L=1,NM),(CLADYSS(L),L=1,NM),(COBLEKTE(L),L=1,NM),
*(COLMSFLX(L),L=1,NM),(COLPE(L),L=1,NM),
*(COLGL(L),L=1,NM),(CRTHTFLX(L),L=1,NM),(CTEMP(L),L=1,NM),
*(EFCLADSS(L),L=1,NM),(ELEV(L),L=1,NM),
*(FSDSP(L),L=1,NM),(FSTEMP(L),L=1,NM),(GAPHTC(L),L=1,NM),
*(GAPPR(L),L=1,NM),(HEATTRMD(L),L=1,NM),
*(IOXTN(L),L=1,NM),(LOCRODPW(L),L=1,NM),(METWRE(L),L=1,NM),
*(OOXTN(L),L=1,NM),(OXSTN(L),L=1,NM),
*(STRUCIP(L),L=1,NM),(STRUCRG(L),L=1,NM),(SURHTC(L),L=1,NM),
*(SURHTFLX(L),L=1,NM),(THMGAPIP(L),L=1,NM),
*(THMRG(L),L=1,NM),
*RPMFS,RPMCI,RPMMX,MIDTEMPP,FAILFLAG,
*(DATA1(L),L=1,NM1)

DO I=1,NM
RPMFS(I)=DATA1(1+(I-1)*5)*1000.
RPMCI(I)=DATA1(2+(I-1)*5)*1000.
RPMMX(I)=DATA1(3+(I-1)*5)*1000.
MIDTEMPP(I)=DATA1(4+(I-1)*5)
FAILFLAG(I)=DATA1(5+(I-1)*5)
ENDDO

IF(ISW.EQ.0) THEN
ISW=ISTEPPRINT
TT=DATAINT(1)
DTT=DATAINT(2)
IB=IB+1
WRITE(*,*) 'TIME=', TT, 'TIME STEP=', DTT, IB
WRITE(2,4) TT,(DATAINT(K),K=1,13)
WRITE(3,4) TT,(CLADAXSS(K),K=1,NM)
WRITE(4,4) TT,(CLADHSN(K)*100,K=1,NM)
WRITE(5,4) TT,(CLADHSS(K)*10.,K=1,NM)
WRITE(6,4) TT,(CLADITE(K),K=1,NM)
WRITE(7,4) TT,(CLADOTE(K),K=1,NM)
WRITE(8,4) TT,(CLADPASN(K)*100,K=1,NM)
WRITE(9,4) TT,(CLADPHSN(K)*100,K=1,NM)
WRITE(10,4) TT,(CLADPRSN(K)*100,K=1,NM)
WRITE(11,4) TT,(CLADRSN(K)*100,K=1,NM)
WRITE(12,4) TT,(CLADSNI(K)*100,K=1,NM)
WRITE(13,4) TT,(CLADSSI(K),K=1,NM)
WRITE(14,4) TT,(CLADYSS(K),K=1,NM)
WRITE(15,4) TT,(COBLEKTE(K),K=1,NM)
WRITE(16,4) TT,(COLMSFLX(K),K=1,NM)
WRITE(17,4) TT,(COLPE(K),K=1,NM)
WRITE(18,4) TT,(COLGL(K),K=1,NM)
WRITE(19,4) TT,(CRTHTFLX(K),K=1,NM)
WRITE(20,4) TT,(CTEMP(K),K=1,NM)
WRITE(21,4) TT,(EFCLADSS(K),K=1,NM)
WRITE(22,4) TT,(ELEV(K),K=1,NM)
IF(IB.EQ.1) RPMFS0=RPMFS(1)
IF(TT.GE.0. AND . ITT.EQ.0) THEN
DO L=1,NM
FDISO(L)=FSDSP(L)*100./RPMFS0
IF(FDISO(L).LE.0.000001) FDISO(L)=0.
ENDDO
ITT=ITT+1
ENDIF
WRITE(23,4) TT,(FSDSP(K)*100./RPMFS0-FDISO(K),K=1,NM)
WRITE(24,4) TT,(FSTEMP(K),K=1,NM)

```

```

      WRITE(25,4) TT,(GAPHTC(K),K=1,NM)
      WRITE(26,4) TT,(GAPPR(K),K=1,NM)
      WRITE(27,4) TT,(HEATTRMD(K),K=1,NM)
      WRITE(28,4) TT,(IOXTN(K),K=1,NM)
      WRITE(29,4) TT,(LOCRODPW(K),K=1,NM)
      WRITE(30,4) TT,(METWRE(K),K=1,NM)
      WRITE(31,4) TT,(OOKTN(K)*1000.-3.,K=1,NM)
      WRITE(32,4) TT,((OXSTN(K)+OOXTN(K))*1000.-3.,K=1,NM)
      WRITE(33,4) TT,(STRUCLP(K),K=1,NM)
      WRITE(34,4) TT,(STRUCRG(K),K=1,NM)
      WRITE(35,4) TT,(SURHTC(K)/1000.,K=1,NM)
      WRITE(36,4) TT,(SURHTFLX(K)/1000.,K=1,NM)
      WRITE(37,4) TT,(THMGAPIP(K),K=1,NM)
      WRITE(38,4) TT,(THMRG(K),K=1,NM)
      WRITE(39,4) TT,(RPMFS(K),K=1,NM)
      WRITE(40,4) TT,(RPMCI(K),K=1,NM)
      WRITE(41,4) TT,(RPMMX(K),K=1,NM)
      WRITE(42,4) TT,(MIDTEMPP(K),K=1,NM)
      WRITE(43,4) TT,(FAILFLAG(K),K=1,NM)
      ENDIF
      ISW=ISW-1
      ENDIF
      GOTO 2
1 FORMAT (A18)
4 FORMAT (1P50E14.6)
3 CONTINUE
      STOP
      END

```

APPENDIX B. The revealed mistakes

1. Zero values of the pressure in the gas accumulator saved in the output STRIPF file.

In STORE6 subroutine the procedure of saving gas pressure into the STRIPF output file has been changed. Prior to calling for GRAFOUT subroutine, the following string was inserted:

TP(1)=TPLNA(1,2,1).

2. TUNING subroutine controls the input data block option, which specifies the multiplication factors for some physical parameters. It was revealed that the suboptions were not suitable for numerical tuning apart from the following suboptions:

- Fuel thermal conductivity;
- Pool boiling heat transfer coefficient;
- Free convection heat transfer coefficient;
- Critical heat flux.

Other suboptions are apparently in disagreement with the FORTRAN format specifications.

3. Critical heat flux (PCHF subroutine)

To calculate critical heat flux subcooling factor is used in the following form:

$$F_S = 1 + 0.065 (\rho_f / \rho_g)^{0.8} \Delta I / h_{fg},$$

where ρ_f and ρ_g = water and steam densities;

h_{fg} = latent heat;

g = gravity acceleration;

ΔI = difference between enthalpy of the liquid saturation and fluid bulk temperature.

In the text of the code the subcooling factor is expressed as follows:

$$FSUBC = 1.00+0.065D0*((RF/RG)**0.8D0)*(CPF*DTSUBF/(HGP-HFP)),$$

where $\Delta I = CPF * DTSUBF$, CPF - specific heat of fluid and DTSUBF - subcooling temperature).

Calculations in the PCHF subroutine are performed in the British Thermal Units (BTU). Still, subcooling temperature is presented in the SI system. The mistake was eliminated by converting DTSUBF parameter from Kelvin to Fahrenheit.

4. Ross and Stout model to calculate gas gap thermal conductivity (GAPHTC subroutine):

The following formula is used to calculate thermal conductivity of the non-zero fuel-cladding gap:

$$\alpha_g = \frac{\lambda_{gas}}{\Delta_g + C(R_f + R_c) + (g_f + g_c)},$$

where λ_{gas} = thermal conductivity of the gas mixture in the gap (W/m K);

Δ_g = fuel-cladding gap in the hot state (m);

R_f = mean arithmetic of the fuel roughness value (m);

R_c = mean arithmetic of the cladding roughness value (m);
 C = empirical constant;
 $g_f + g_c$ = temperature jump distance at the external fuel surface and at the internal cladding surface, respectively.

In the text of the subroutine this is expressed as:

$$hgap = gpcon/(gpthk + gjmpft + drough),$$

where $gpcon$ = thermal conductivity of the gas mixture in the gap;

$gpthk$ = fuel-cladding gap in the hot state;

$gjmpft$ = $g_f + g_c$;

$drough$ = $C(R_f + R_c)$ mean arithmetic of the fuel roughness value (m).

In the subroutine the complex is calculated as:

```
DROUGH = FROUGH*(RUFF+RUFC)/12.D0  
RUFF = R_f; RUFC = R_c; FROUGH = C
```

Still, the condition under which the fuel-cladding gap can not be less than $C(R_f + R_c)$ value was already specified as:

```
THKMIN = 3.6D0*(RUFF+RUFC)/12.D0  
IF (GPTHK.LT.THKMIN) GPTHK = THKMIN
```

This leads to the mistake in calculating thermal conductivity of the fuel-cladding gap according to the Ross and Stoute model. That is why the condition «IF (GPTHK.LT.THKMIN) GPTHK=THKMIN» was taken out of the text of GAPTHC subroutine.

BIBLIOGRAPHIC DATA SHEET

(See instructions on the reverse)

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Code for High Burnup VVER Fuel

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11. ABSTRACT (200 words or less)

The USNRC's transient fuel rod code, FRAP-T6, has been modified to analyze pulse tests with high burnup VVER fuel rods in the Impulse Graphite Reactor (IGR). New and modified models of separate phenomena have been developed, including models for heat transfer from the cladding to the stagnant coolant, the effect of fission gas swelling on the fuel cladding gap, and the conditions of base irradiation. Thermal and mechanical properties for the VVER's Zr-1%Nb cladding were added to MATPRO-V11, which is used by the FRAP-T6 code. Changes in the input data file are described and a sample calculation is presented with the modified code. A FORTRAN listing for the new and modified models is given in an Appendix A.

12. KEY WORDS/DESCRIPTORS (List words or phrases that will assist researchers in locating the report.)

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